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THE CREATED STONE: CHEMICAL AND ARCHAEOLOGICAL PERSPECTIVES ON THE COLOUR AND MATERIAL PROPERTIES OF EARLY EGYPTIAN GLASS, 1500 – 1200 B.C.

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THESIS CONTAINS

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"The gods may derive their colour and beauty from the high splendours of nature, but it was Man who obtained these for them, abstracted them from sun and moon and cloud..."

J.R.R. Tolkien, *On Fairy-Stories*

Abstract

The Late Bronze Age in Western Asia and Egypt witnessed an explosion in the production of so-called 'vitreous materials', in particular the earliest glass. From its outset, this material appeared in an enormous variety of colours and colour combinations, the manufacture of which demanded a high degree of technological know-how. The unique properties of glass also rapidly came to the fore, most notably the potential of glass to be worked while hot.

Archaeometric research into early Egyptian glass has tended to focus on chemical and isotopic analysis as a means to assign provenance to its raw ingredients. To this end, the use of a technique new to archaeology, ToF-SIMS, is developed here in order to investigate the origin of the colorant-opacifiers used in glass production. But questions about manufacturing technology and stages of production are also vital to an understanding of the role and perception of glass, and the aforementioned technique is complemented by electron microprobe analysis, revealing a surprising complexity of production, primarily related to coloration.

Furthermore, it has been argued that the terms used to refer to glass in epigraphic sources indicate that it was primarily produced in order to imitate, or substitute for, precious stones of value in Late Bronze Age Egypt and Mesopotamia (primarily lapis lazuli, carnelian and turquoise). Recent research into the archaeological and ethnographic understanding of colour naming and classification is applied to these sources along with an investigation of the material properties of glass itself. It is suggested that, far from being an imitation, the artificiality of glass – as a man-made material – was deliberately, sometimes spectacularly, proclaimed. Central to this is the use of colour, in particular in terms of transformation, and the aforementioned complexity of production. It is argued that only through combining the numerous approaches to the evidence taken here – scientific, linguistic-historical, and archaeological – can the perception of glass, and the motivations behind its production, be determined.

Acknowledgements

This thesis could not have been written without the assistance or support of a number of other people. Professor Julian Henderson of the University of Nottingham has provided supervision and guidance, and first inspired me as an undergraduate to take an interest in looking through a glass, darkly. He also liaised with the directors of excavations at Tell Bazi and Deir 'Ain 'Abata to provide samples for this study and was the first to realise the potential of ToF-SIMS for characterising ancient glass. Dr. Lloyd Weeks, University of Nottingham, has also offered invaluable support, advice and a sense of humour, as well as instructing me in the use of PCA. I have also been very lucky to undertake my studies in a lively and generous community of staff and postgraduates at the University of Nottingham.

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To my long suffering friends – those involved in archaeology who have listened to me rambling on about glass, and all those outside archaeology who have listened to me rambling on about digging – thank you, for everything. To my family, who have always been there for me and never once asked when I'll get a proper job, I am forever grateful.

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Contents

List of Abbreviations

Common Abbreviations Used in Text and Tables:

BA	Burst Alignment
BM	British Museum
BSE	Back Scattered Electron
EA	Egyptian Antiquities (British Museum catalogue)
EDX (or EDS)	Energy Dispersive X-ray Analysis
EPMA	Electron Probe Microanalysis
HCB	High Current Bunched
HMG	High Magnesia
ICP-AES	Inductively Coupled Plasma Atomic Emission Spectroscopy
ICP-MS	Inductively Coupled Plasma Mass Spectrometry
LA-ICP-MS	Laser Ablated Inductively Coupled Plasma Mass Spectrometry
LBA	Late Bronze Age
LIA	Lead Isotope Analysis
LMG	Low Magnesia
LMIG	Liquid Metal Ion Gun
LMHK	Low Magnesia High Potash
MAA	Cambridge University Museum of Archaeology and Anthropology (also CUMAA)
MMA	Metropolitan Museum of Art
PCA	Principal Components Analysis
PDMS	Polydimethylsiloxane
RDS	Raw Data Stream
ROI	Region of Interest
SE	Secondary Electron
SEM	Scanning Electron Microscopy
SIMS	Secondary Ion Mass Spectrometry
TEM	Transmission Electron Microscopy
ToF-SIMS	Time of Flight Secondary Ion Mass Spectrometry
WDX (or WDS)	Wavelength Dispersive X-ray Spectrometry
Z	Atomic number

Chemical Elements Mentioned in Text and Tables and their Symbols:

Aluminium	Al	Lithium	Li	Vanadium	V
Antimony	Sb	Magnesium	Mg	Zinc	Zn
Arsenic	As	Manganese	Mn	Zirconium	Zr
Bismuth	Bi	Neodymium	Nd		
Cadmium	Cd	Nickel	Ni		
Calcium	Ca	Oxygen	O		
Carbon	C	Phosphorus	P		
Chlorine	Cl	Potassium	K		
Chromium	Cr	Scandium	Sc		
Cobalt	Co	Silicon	Si		
Copper	Cu	Silver	Ag		
Gallium	Ga	Sodium	Na		
Gold	Au	Strontium	Sr		
Hydrogen	H	Sulphur	S		
Iron	Fe	Tin	Sn		
Lead	Pb	Titanium	Ti		

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1. Introduction

> "Vitreous materials are often regarded as an area of extreme archaeological specialisation, the preserve either of archaeological scientists or of archaeological masochists."
>
> Susan Sherratt 2008

It would not be unfair to say that current perceptions of Late Bronze Age glass tend to be somewhat affected by the reputation of its technological descendants. Later developments such as glass blowing and decolouration, our linguistic and symbolic associations of glass and the uses of glass in recent history (as windows, lenses, and drinking vessels) have to some extent obscured the complex reality of the earliest glass production, at least to those not directly involved in its archaeological investigation.

Misconceptions about glass may in part be due to the nature of the material itself. It is scientifically defined by its microstructure rather than its chemistry, yet it is on the basis of chemistry which it is principally studied and understood; its utility is commonly associated with its ability to transmit light, but the earliest glass was opaque; knowledge of glass making, and to a lesser extent working, has belonged to a relatively closed group of artisans throughout its history, but in many periods glass was seen as a relatively abundant and cheap material; and the means by which glass making was discovered may have been so complex that it is thought to have occurred only once, with all subsequent production deriving from the person to person handing down of that initial leap of knowledge.

To some extent the same mystery surrounding the production of glass in the past persists in the way it is studied archaeologically, in part perhaps because it demands the consideration of a number of seemingly disparate threads of knowledge. In order to understand the making, working and corrosion of glass, some knowledge of its chemistry and physical structure is vital. Much of the published work about glass thus focuses on chemical analysis and the provenance of its raw ingredients. Furthermore glass is almost exclusive to historical periods, so that some consideration of its textual and linguistic referents is also required in providing a comprehensive study of the material in almost any of the periods and places in which it is found. Added to this, of course, are archaeology's usual suspects: typology, deposition and context of use.

I thus set out to explore the production and role of Egyptian glass in the Late Bronze Age (LBA) from several perspectives: scientific, linguistic-historical and archaeological. During the course of my research, however, I found that I always came back to colour.

Colour is intrinsic to the relationship between glass and the precious[1] stones it has been described as imitating; the chemical analysis of glass and the difficulties involved in the production of various colours; and questions of production locations and the stages involved in glass manufacture. Thus colour forms a central focal point or nucleus, from which branch other issues and questions about glass (in particular in LBA Egypt), and about the study of colour and material properties in general.

Aims

This study is an attempt to provide a better understanding of some of the earliest production and use of glass. The material itself is taken as a starting point, and its properties are considered from a range of approaches with the aim of providing complementary analyses of glass from scientific, historical and archaeological perspectives. The focus is on Egyptian glass, which provides the majority of the analysed material for this thesis, but the technological and cultural interactions between Egypt and other areas are also relevant to any discussion of the Late Bronze Age. Likewise, the chemical difference between glass across regions and over time provides an important context for analysis. Thus other areas involved in glass production and use are also discussed, and some post-Bronze Age examples of Egyptian and Mediterranean glass have been analysed with the electron microprobe (for details see Chapter 2 and Appendix 1), providing a broader context for interpretation.

The specific questions addressed are as follows: how was glass perceived as a material, and what is its relationship with other material categories and perceptions? Can we truly describe glass as an 'imitation' or 'substitute' for precious stones? How do we define colour and the role of colour in these perceptions? How complex and specialised were the colouring and manufacturing technologies, and how might this relate to the perception and value of glass? What is the evidence for access to, and control over, resources in glass production? Did the artificial nature of glass affect its value and if so, how?

The above questions are intended to provide insights into glass production and consumption, but they are also pertinent to archaeological understanding of the development and perception of new materials in general. Questions of why and how new technologies are developed and maintained are of interest to a wider range of topics of archaeological investigation. In this vein, I also aim to develop avenues for the integration

[1] For the purposes of the present work, the term 'semi-precious stone' as commonly used today to describe the sorts of stones valued during the Late Bronze Age, will be abandoned. I use the term 'precious stone' to refer to those stones which were of value in the period involved, avoiding the ambiguities of inflicting rather cumbersome modern terminology upon stones which were, after all, not semi- but fully precious during the period in question. The stones to which the term refers are most prominently represented by turquoise, amethyst, lapis lazuli, carnelian, and obsidian. Others – stones such as serpentite which were not quite as highly valued but could be worked and prized for their visual properties – are referred to by name or under the general heading of 'stone'.

of chemical analytical research with those questions which are traditionally seen as less accessible by scientific means. The discussions of analytical results are aimed at providing a better understanding of glass from the selection of raw materials through to the production of the final coloured material. For example, determination of the raw ingredients and the production technology involved in making certain colours of glass – addressed with Electron Probe Microanalysis (EPMA) and Time of Flight Secondary Ion Mass Spectrometry (ToF-SIMS) – is vital to interpreting the way in which glass production was organised, and the value of coloured glass.

Thus the questions asked of the material are always related to those topics which might help us to better understand the relative position, value and perception of glass. As argued by Sherratt and Sherratt (2001, 18), the history of consumption – the role of demand, understanding *why* people want particular material goods – is now recognised as being as vital as the history of production. In particular, the results presented here are to some extent bound up with consideration of the impact and perception of new (particularly artificial or transformed) materials. A secondary aim of the present study, then, is to investigate the means through which questions of materials and materiality (see below) are addressed, with a particular focus on the study of colour, and with wider resonance for archaeological investigation.

Theoretical Approaches

Martinón-Torres (2008) notes the entanglement of materials, products and 'agents' within specific historical conditions and value systems: human behaviour mixes components that are often heuristically separated, such as technology, subsistence, society and culture. Material culture, however, is intrinsic to all, and the approach taken here is in keeping with elements of the theoretical stance known as materiality. Materiality, notes Timothy Taylor, is a style of inquiry that engages with the unavoidable qualities of a material and 'encourages reconstruction of past categories and classifications, allowing an appreciation of why the essential 'thingness' of things ... is not just good for thinking, in the sense of providing poetic or metaphorical resources, but underpins the ability to think, by providing the cultural framework of concrete exemplars from which metaphysical categories can be abstracted' (Taylor 2008, 297). In other words, materiality places the tangible qualities of things, sometimes referred to as their *affordances*, at the centre of archaeological investigation, and encourages the use of these in reconstructing broader cultural features of past societies, including those which – under the dictum of the 'Hawkes' ladder' approach – would be thought of as beyond comprehension on the basis of material remains (such as aspects relating to religion or ritual). Indeed, the theoretical stance of materiality was initially instigated as an antidote to purely evolutionary and later textual models which reduce the place of artefacts to arbitrary signifiers or reflectors of social interaction: it is thus recognised that material culture can also be integral to the

development of concepts and does more than passively reflect them (Taylor 2008, 312 – 313; Boivin 2005, 175). At its core, then, materiality seeks to investigate the two-way interaction between humans and materials.

Addressing materiality, of course, is much more difficult than simply defining it. Values are central to themes of materiality, yet values are often difficult to disentangle. Defining the significance of material properties requires as broad a contextual consideration as possible, and this is attempted through the multiple approaches taken in the present work. It is recognised that addressing the interaction between the perception and the affordances of things can be reasonably constrained by a cautious appeal to plausibility. The shininess of glass is not likely to confer symbolic properties of darkness onto the material, for example, although we should always bear in mind that such symbolism may come to be associated with the material through other, more complex paths of reference. The existence of textual sources for the period under consideration is beneficial in that they contribute to the restriction of what can be plausibly suggested. As will be discussed, however, the textual sources must be treated with caution and examined with reference to archaeological evidence to avoid misinterpretation. An example of good method in approaching the interaction between people and the material world is the work of Dorothy Hosler (1994; 1995) on the use of metals in historic Mexico: Hosler focuses on the material, investigating how the qualities and perception of metal affect the Mesoamerican world view, as well as how this world view affects the production of the metals themselves.

Furthermore, it has been suggested that materiality can integrate what might be described as the often incompatible approaches of contemporary theoretical stances and archaeometry (see Jones 2004). Materiality, suggests Jones, encompasses the view that material or physical components of the environment and the social practices enacted in that environment are mutually reinforcing, and are therefore analytically indivisible.

Despite the value of integrating approaches, of course, the differences between the three key sources of evidence used here – scientific (here, chemical analysis), archaeological (in the sense of artefact- and context- focused research) and textual (epigraphic) sources – do require some consideration. Interpretations of the textual evidence in particular often produce more contradictions than conclusions (see Lilyquist 2005), and some of the arguments to be presented centre on what appears to be something of a misreading of the linguistic evidence for colour terms which has, I argue, led to the erroneous conclusion that glass was produced primarily as a lower value imitation of precious stones. In a wider context it might be stated that much work is yet to be done in order to overcome the past focus on language as the primary or only vehicle for communication (see Schiffer 1999, 30 - 50). As argued by Moreland (2001, 90 - 97), however, the recent backlash against the

'tyranny' of historical over archaeological sources is no remedy to the misinterpretations effected by the former.

In this study, then, the various sources of information have not been ranked hierarchically, but certain among them have been more heavily weighted. This is in part because of their differential relevance to the study at hand, but my own field of interest has also, perhaps inevitably, been investigated more fully, while in other areas previously published work has been more heavily relied upon. Not being an epigraphist myself, the textual evidence is based on the compilation of a number of published works which have not (to my knowledge) been combined previously in relation to glass. The archaeological evidence also involves an in-depth discussion of previous thoughts and ideas on the subject, but here more primary data is included, including a survey of colour use in Late Bronze Age glass objects. Recent theoretical developments in the study of colour are also applied here to glass, and these provide a tying together of material and textual evidence. The archaeometric evidence is more firmly rooted in primary investigation, but even here the broad background consideration of other sources of evidence is vital for its application to questions of archaeological relevance.

It has thus been necessary to look for several methods of extracting as much information as possible from the material itself, allowing the convergence of the different approaches so that each may be discussed with reference to the conclusions of the others. The difficulties of using the broad range of approaches adopted here are thus intended to be counterbalanced by the tight focus on the material itself.

Structure

The main body of the text which follows can be broadly divided into three parts, concluding with a discussion (Chapter 7) which is aimed at uniting the different elements focusing on understanding the role, perception and production of glass in LBA Egypt.

The first part includes Chapters 2 and 3 and provides a background to both the material investigated and the current state of knowledge. Chapter 2 includes a broad background to Egypt and her neighbours during the Late Bronze Age, a discussion of the arrival of glass in Egypt with a brief list of categories of glass object, followed by details of the sampling strategy for analytical techniques and an outline of archaeological sites of relevance to the study. Chapter 3 provides an overview of the existing chemical evidence for colouration in glass, followed by an examination of recent theoretical approaches to the study of colour, both of which are intended as a background or prelude to the material presented in parts two and three.

Part two consists of all four sections of Chapter 4 and forms the primary archaeological and textual (linguistic) investigation. This investigation is divided into the questions asked of the material, rather than specific approaches: the colours of glass and the role of colour and material in Egyptian systems of reference are considered first, followed by a section on the value of glass and a then by a more detailed discussion of its material properties. Finally, blue glass is focused upon as a specific case study, presenting the role of colour in glass perception and value with reference to the forms of evidence discussed in the previous three sections.

Part three includes Chapters 5 and 6, dealing with the chemical analytical evidence and results. Chapter 5 is based on the investigation and results of EPMA and image analysis. Here, the results are rooted in a broader context due to the examination also of samples from outside of Egypt, and some from the 1st millennium B.C. Evidence relating to manufacturing technology is also presented in Chapter 5 and, perhaps most significantly, it is argued that a limited amount of recycling was practised in LBA Egyptian glass production. Chapter 6 includes a lengthy discussion of the application of ToF-SIMS to the analysis of four samples of LBA glass from Egypt, Syria and Greece. The optimisation and methodology of the application of this novel technique to archaeological material are considered in some detail, along with some promising evidence towards a better understanding of the source of raw ingredients in glass production and the associated manufacturing technology of certain colours.

Chapter 7 provides discussion of the results and suggestions presented in the previous three parts of the thesis in order to draw archaeological inferences and – it is hoped – illustrate that the combination of different forms of evidence can be used to good effect in archaeological investigation.

The primary data discussed in the text can be found in the appendices. Appendix 1 is the catalogue of samples used in the analytical portion of the study. Appendix 2 provides the tables of results for EPMA and image analysis, and the primary data from which the survey of colour use in finished glass (Chapter 4) was derived. Appendices 3 and 4 are photographs of the items sampled and microscopic images of samples respectively, and can be found in the attached CD.

2. Archaeological Background and the Material Studied

2.a. Egypt in the Late Bronze Age and the Spread of Glassmaking Technology

The main focus of both the analytical and theoretical / archaeological aspects of this thesis is on Egyptian material dating from approximately 1500 to 1200 B.C., i.e. within the period defined for this region as the 'Late Bronze Age'. The latter is the most commonly used term here when referring to the period under discussion, but where it is more accurate (for example, when discussing artistic developments), a particular Dynasty (e.g. XVIII), or regional classification (e.g. Old Babylonian) will be referred to. Absolute dates (B.C.) are also used throughout, in conjunction with these classifications, and a summary of the chronology of the period is illustrated in Figure 2.1. A broad background to Egypt in the Late Bronze Age is provided below, followed by an outline of the state of knowledge on the inception of glass and its arrival in Egypt, and the typical object categories which are associated with glass of this period. Further details of some of the archaeological sites mentioned below can be found in the second part of this chapter.

Egypt in the Late Bronze Age

As noted by Moorey (2001, 12), Egypt is 'somewhat isolated geographically'. The principle sites of Egypt are situated on the eastern and western banks of the River Nile, and in the Nile Delta (Lower Egypt). Aside from the cultivated area around the Nile, Egyptians had access to a wide range of natural resources in the Eastern Desert and Red Sea coast, in the Western Desert and its oases, and in the western and southern parts of the Sinai peninsular (see Waldbaum 1978, 65). These included clay, sandstone and limestone, copper, gold, galena, turquoise, carnelian, quartz, jasper and serpentine. Imported commodities included timbers from the Levant, incense and myrrh from the Arabian peninsula, silver from northern Syria and lapis lazuli obtained via Mesopotamia.

With the expulsion of the foreign Hyksos Dynasty and the beginning of the XVIII Dynasty in the mid sixteenth century B.C., Egypt entered a phase of military expansion which somewhat decreased her traditional isolation. Egyptian territories were extended into Nubia to the south and – gradually – to the smaller city states of Syria and Palestine to the north-east (Murnane 2000, 702; Lemche 2000, 1207).

Absolute Dates (B.C.)	Egypt		Assyria	Babylonia	Hatti	Mittani
1595	Second Intermediate: 15th - 17th Dynasties (1640 - 1540)			Fall of Old Babylon (1595)	Mursili sacks Babylon (1595)	
1540		Amenhotep I (1525 - 1504)				Šuttarna I
		Tuthmosis I (1504 - 1492)				Parattarna
1500 (Annales of Tuthmosis III, Karnak)						
1450		Tuthmosis III (1479 - 1427)	Aššur-nadin-ahhe (c.1440)			
		Amenhotep II (1427 - 1400)	Aššur-bel-nišešu (1417 - 1409)			Artatama
1400		Tuthmosis IV (1400 - 1390)				Šuttarna II
		Amenhotep III (1390 - 1352)		Kadašman-Enlil (1374 - 1360)		Artaššumara
1365 - 1335 (Amarna Archives)		Amenhotep IV (Akhenaten, 1352 - 1336)	Aššur-uballit (1363 - 1328)			Tušratta
	New Kingdom: 18th - 20th Dynasties (1540 - 1070 B.C.)	Tutankhamen (1335 - 1323)		Burnaburiaš II (1359 - 1333)	Suppiluliuma I (1344 - 1322)	Šuttarna III
			Adad-nerari I (1305 - 1274)			Šattiwaza
1300					Mursili II	Šattuara I
1274 (Battle of Qadesh)			Shalmaneser I (1273 - 1244)	Kadashman-Enlil II	Muwatalli II	Wasašatta Šattuara II
		Ramesses II (1290 - 1224)				
1259 (Peace Treaty Between Egypt and Hatti)					Hattusili III	
			Tukulti-Ninurta I (1243 - 1207)			
1200 (Fall of Mycenae; Fall of Hatti; Sack of Ugarit)		Merneptah (1224 - 1214)		Kashtiliashu IV	Tudhaliya IV	
					Suppiluliuma II	
		Ramesses III (1194 - 1163)	Assur-resha-ishi I	End of Kassite Dynasty (1155)		
1070	Third Intermediate: 21st - 25th Dynasties (1070 - 712 B.C.)		Tiglath-pileser I	Nebuchadnezzar I		
...						

Figure 2.1 Historical and Absolute Chronology.

For the sake of brevity, not all kings' names are included. Information taken from Van de Mieroop (2007, 131); Bryce (1998, 375); Oates et al. (1997); Kemp (1989b, 14); and Baines and Málek 1984. The Late Bronze Age is generally classified as lasting from ca. 1550 to ca. 1150 B.C., at least in those areas under strong Egyptian influence (see Strange 2001, 293 - 294).

Thus Egypt at this time may be characterised as one of the so-called 'great powers' (see Liverani 2000) which in the fifteenth century B.C. also included Hatti (the kingdom of the Hittites), Mitanni and Babylonia (Charpin 2000, 819). As illustrated in Figure 2.2, the struggle for territories between these powers was ongoing, with Egypt at times gaining

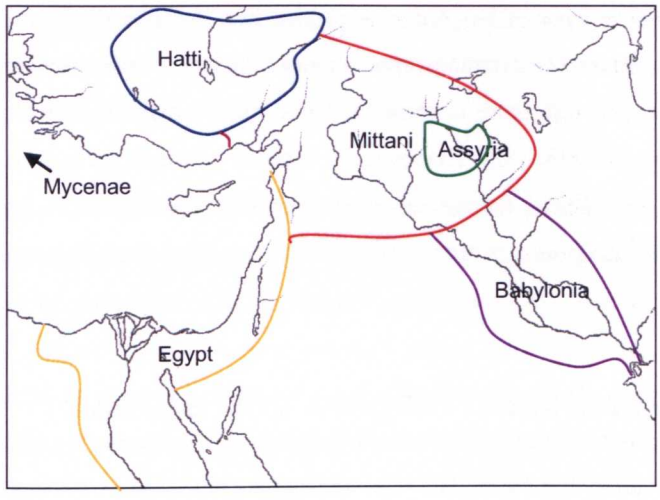
land from, or ceding it to, one or other of her neighbours (see Lemche 2000, 1206). By the end of the fourteenth century Mitanni had all but disappeared with her former lands being largely occupied by Assyria, which expanded significantly under Assur-uballit (1366 - 1330), while Hatti had vastly increased her territories. To the periphery of the areas under consideration were other powers: the kingdom of Elam to the east, and Mycenaean Greece. The latter may not have been as wealthy or influential as the core group of great powers, yet Hittite king Khattushili III addresses its ruler as a great king, his brother and equal in diplomatic correspondence of the thirteenth century B.C. (Macqueen 2000, 1095).

Related to the military conflicts characteristic of the great powers in Egypt and Western Asia, there existed a network of international contacts during the Late Bronze Age which was previously unparalleled in the region (Moorey 2001, 2 – 3). Diplomatic correspondence is attested in tablets recovered from a number of sites including Amarna in Egypt (see below), Boghazköy in Anatolia, and Alalakh and Ugarit in the Levant. Hand in hand with this correspondence was the practice of long distance gift exchange between the great powers and tribute from smaller city-states and vassal kingdoms to their ruling powers.

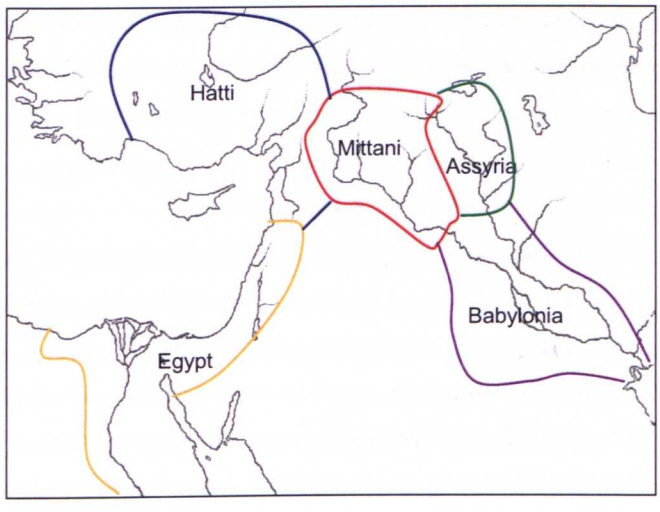
The wealth thus flowing into Egypt during the New Kingdom increased the powers of the king, and the centralisation of government (Leprohon 2000, 283). Transactions including the exchange of raw materials, worked objects and people (such as marriageable women and craftsmen) are attested in the Amarna letters of the mid fourteenth century B.C. (see Moran 1987; Westbrook 2000), and in reliefs depicting the bringing of captured slaves and booty, or tribute to Egyptian kings (see Lilyquist 2005).

From approximately 1200 B.C. widespread disruption occurred in Western Asia and the eastern Mediterranean. Accounts of the time appear to relate this to migratory movements, though the reality is probably rather more difficult to disentangle. It is known, however, that groups of Aramaean nomads laid waste to the main sanctuaries of Babylonia, which finally fell into chaos towards the end of the eleventh century (Charpin 2000, 821) while the previously growing power of Assyria was reduced to defending its heartland for most of the 12th century B.C. (Van De Mieroop 2007, 196). The Hittite state, which had always had difficulty in maintaining its many land borders, suffered total collapse by the end of the 13th century B.C. due to a combination of invasions and internal conflicts as well as possible harvest failure due to climate change (Macqueen 2000, 1097). The so-called 'Sea Peoples' were held responsible for the destruction of city-states such as Ugarit (Charpin 2000, 821), though this is also linked with the decline of their neighbouring powers. The Mycenaean culture rapidly declined in the Aegean, as illustrated by the disappearance of the Linear B script, the partial abandonment of settlements and a decline in evidence for trade with the outside world (see Dickinson 1994, 87).

a.



b.



c.

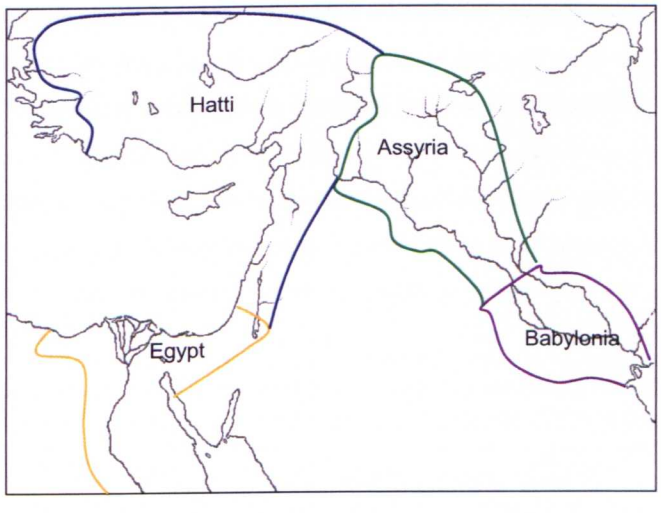


Figure 2.2 Regional Power during the Late Bronze Age.
The shifting spheres of control of the 'Great Powers' in:

a. ca. 1450 B.C.
b. ca. 1350 B.C.
c. ca. 1220 B.C.

For ease of reference neighbouring kingdoms (including Elam and Arzawa) and smaller city states not mentioned in the text have been omitted.
After Van de Mieroop (2007, 132).

Although Egypt remained relatively wealthy at this time, in part due to her vast natural resources, control over most of her Asian territories was lost and Egyptian contact with most areas of the eastern Mediterranean and inland Palestine deteriorated sharply during the late 12th century, though there is some evidence for the maintenance of contact with the Levant (Weinstein 1998, 188). Evidence for internal conflicts during the 12th century B.C., culminating in political fragmentation in approximately 1100 B.C. may also have been related to the disruptions to trade and political ties (Van Der Mieroop 2007, 196 - 197).

The Earliest Glass: origins and spread

It is generally accepted that glass was first produced deliberately and consistently sometime between c.1650 and 1550 BC (see for example Oppenheim 1973b; Lilyquist and Brill 1993; Mass et al. 2002; Tite and Shortland 2003). There is some scattered evidence for prior glass production, largely in the form of beads (see Grose 1989, 45), but much of this material was most likely the by-product of other pyrotechnological processes, notably faience production and metal smelting, the latter often resulting in highly coloured glassy slags, examples of which can be dated back as far as the third millennium B.C. (Schlick-Nolte and Lierke 2002, 15). Faience[2] consists of a fused core of granular quartz or sand, with sufficient alkali and associated impurities to produce a rigid vitreous or semi-vitreous surface: it was typically composed of approximately 93 – 98% crushed quartz, 1 – 5% lime and 0.5 – 3% alkali flux, though there were a number of variations on and developments of the basic product and the colours of the glaze (see Kaczmarczyk and Hedges 1983, 6 - 10). In its essentials, however, faience was made from the same basic ingredients as glass (see Chapter 3), albeit in very different proportions. Lilyquist and Brill (1993, 18) provide a chart illustrating the physical-compositional differences in various types of faience, frit, the Egyptian blue pigment and glass (see also Brill 1963). The origins of primary glass production have been discussed elsewhere (see Tite et al. 2002; Lilyquist and Brill 1993; Engle 1973; Bimson and Freestone 1992), and this is not the place for a detailed consideration of its technological antecedents. It should suffice to note that faience production and metal smelting, as high temperature industries with related ingredients and / or products, are both likely to have contributed to a greater or lesser extent to the first primary production of glass on a consistent basis.

Despite links between primary glass production and other applications of pyrotechnology it appears that the very first glass (in contrast to metal of the same period) was not cast or worked while hot. Instead, the principles of stone working were applied to the production of the earliest known glass vessels, which treated the pre-formed glass as blanks to be ground and polished. The advent of 'hot-' (as opposed to 'cold-') working followed

[2] Also known as 'Egyptian faience' to distinguish it from the Italian tin-glazed earthenware of the city of Faenza, after which it was originally named.

relatively soon afterwards, at least in Mesopotamia. Now, vessels and beads could be produced by various methods involving coating a removable core of material with glass, and applying trails or blobs of another colour of glass onto this base, a practice known as 'core-forming'[3].

Given the similarities between core-forming glass and the production of faience, which also involved coating a pre-formed core, it is interesting that this was probably not the first method used in the production of glass items. This is significant, because glass and faience are generally referred to by modern scholars under the (scientific) classification of 'vitreous materials', all of which involve the presence of a glassy, homogeneous phase. Apart from glass and faience, this classification includes pigments such as Egyptian blue and even 'Egyptian green' (see Camagna and Colinart 2003) and frit, a sintered combination of the ingredients for glass production created as an intermediary stage in the manufacture of glass, though similar preparations were also ground up for use as pigments.

The earliest evidence for glass in Egypt all points to a Mesopotamian origin. Direct parallels with Mesopotamian material can be found among Egyptian glass from the fifteenth century B.C. Some examples of early glass in Egypt may have been brought into the country following the foreign campaigns of Tuthmosis III in the Levant (Shortland 2001, 213; Oppenheim 1973a, 10 - 11)[4]. Securely dated examples from the fifteenth century include the three colourless name beads (BM EA 26289 and EA 26290; MMA 26.7.746) with inscriptions mentioning Hatshepsut (1473 – 1458 B.C.) and her Steward Senenmut (Nicholson 2007, 1 – 2; Nicholson 2006)[5]. Believed to come from the tomb of the three foreign wives of Tuthmosis III (1479 – 1425 B.C.) is a button-based goblet, comparable in shape and decoration to items from Nuzi (Lilyquist 2005, 63). Similarly, a glass flask (KV 36) from the tomb of Maiherperi, dating to late in the reign of Tuthmosis III, has close parallels in material known from Tell Brak, associated with tablets thought to date to the 15th century BC (Lilyquist 2005, 63).

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[3] It should be noted, however, that the evidence for early glass is sparse. In part this is no doubt due to its poor preservation in most climates (the arid Egyptian climate being particularly, and exceptionally, favourable to the preservation of soda-lime-silica glass). Thus the evidence cannot be said to be completely established. For example, fragments of core-formed glass vessels have been found at Alalakh in levels dating to 1600 BC, suggesting that the knowledge of core-forming was already known in northern Mesopotamia at this early stage (Nicholson 2007, 3). Whatever the precise chronology of early glass working, however, there is a definite transition from the majority of vessels and other items displaying evidence of cold working, to the majority of such items displaying evidence of hot working.

[4] Nicholson (2007, 4 – 5), however, raises some questions as to the security of dating for these vessels.

[5] For more examples of early finds of glass in Egypt the reader is referred to Nicholson (2006) and Nicholson (2007, 1 - 11). The latter publication provides an up to date and detailed summary of glass in Egypt prior to the reign of Akhenaten (Amenhotep IV) and the founding of Amarna in the mid-fourteenth century B.C.

As noted by Moorey (2001, 3), the Hurrian-speaking people of the Kingdom of Mittani are known to have been particularly instrumental in a series of technological innovations during the Late Bronze Age, and it is thought that one of these was the development of glass production. While the impetus for glass making and working may have been theirs, however, the knowledge of this technology soon spread to other parts of Mesopotamia, and to Egypt. Oppenheim (1973b, 263 - 264) has noted that the terms *ehlipakku* and *mekku* thought to refer to glasses are Hurrian and West Semitic respectively, supporting the theory of northern (Upper) Syria as the nexus for glass production.

How exactly the knowledge of glass production was first obtained by the Egyptians is unclear, but given the atmosphere of secrecy surrounding important craft processes (see Moorey 2001, 2) perhaps the most plausible hypothesis which has been put forward is that foreign craftsmen were captured in campaigns (probably those of Tuthmosis III) and led the Egyptian glass working industry (Shortland 2001, 219). Most of the earliest vessels known in the Egyptian style, however, were cold-worked (see Nolte 1968), and it is equally possible that the first glass workers to be introduced came slightly later, perhaps during the reign of Amenhotep II, bringing a fully formed knowledge of core-forming techniques. In any case, glass working was certainly firmly established by the reign of Tuthmosis IV (1400 – 1390 B.C.). This is the first period in which cobalt, obtained from within Egypt, was used extensively as a colorant, suggesting the primary production of glass within Egypt, as well as the first period of the establishment of a standard repertoire of vessel forms (see Nolte 1968).

By the end of the Late Bronze Age glass is found throughout Western Asia, in Egypt and in Mycenaean Greece, and by the dawning of the thirteenth century B.C. glass in different regions had developed localised styles, such as the characteristic relief beads of the Mycenaean world and Minoan Crete (see Panagiotaki 1999; Nightingale 1998), suggesting that glass working was practised locally throughout the regions in which glass is found. The discovery of numerous glass ingots in the cargo of a shipwreck at Ulu Burun, Turkey (see below) suggests that glass was being imported into Mycenaean Greece, and recent isotopic analyses (Henderson et al. 2010) have shown that glass was probably entering Greece from both Mesopotamia and Egypt.

Glass making is thought to be the subject of a series of cuneiform tablets found in the Palace of Assurbanipal (664 – 627 B.C.) at Nineveh[6]. These are copies of original texts written in the twelfth century B.C. or earlier (see Oppenheim 1973b, 265). Moorey (1994, 211 - 212) is cautious in relating these texts to glass, however, and the difficulty in defining the meaning of their (often rare or unique) terminology coupled with the

[6] A transcribed and translated edition of the texts with accompanying photographs, glossary and technical discussion was published by Oppenheim et al. (1970).

complexity of the processes described makes it difficult to resolve the issue: they could feasibly describe the production of faience or pigments.

Categories of Glass Object and Remains

Glass production can be broadly dividing into primary production, that is the fusing of the raw materials at high temperature (glass making) and secondary production, which is more commonly known as glass working and involves the manipulation of the material in either a hot or cold form, in order to produce a finished object. As will be discussed in later chapters, colouring and opacification is not always easy to fit into these categories as it is possible to colour glass during the primary stage, or to add colorants to a preformed glass.

The key categories of glass object for the Late Bronze Age are introduced in turn below, though the categories should not necessarily be seen as mutually exclusive. A useful summary of relevant hot and cold working techniques for glass with accompanying images can be found in Schlick-Nolte and Lierke (2002, 22 – 30).

Evidence for Primary Production

Frit has already been mentioned above. It has been debated whether fritting was practised in the earliest glass production: Jackson et al. (1998), in an experimental reproduction, have illustrated that the fritting stage may not have been necessary in order to make glass, based upon the assumption that this was conducted in crucibles (this interpretation is further discussed in Chapter 4). Cobalt-blue frit was found at Amarna, which may have been a site of primary glass production (see below). The low soda and lime contents of this material, however, have led to the suggestion that it was not produced as an intermediate stage in the production of glass, but in the production of faience (Shortland and Tite 1998, 254 - 257). Refractory and semi-fused remains (the authors do not use the term 'frit') associated with glass production have been found at Qantir (Rehren and Pusch 2005, 1756 - 1757).

Cullet is the term applied to pre-formed glass which is added (or intended to be added) to a primary melt in order to aid the formation of glass. It is thus difficult to distinguish from dumped fragments of broken glass unless found in a context where it can be securely related to other remains of primary production such as frit or furnace linings.

Evidence for Secondary Production

Canes (or rods) and 'spills' of glass are generally associated with the working of raw glass into objects and are thus classified here as evidence for secondary production. Spills are blobs of glass which have fallen during hot manipulation and – usually – made contact with the ground beneath. They are thus characterised by the presence of a main globular form from which a thinner trail extends, though by their nature their shapes are variable.

Figure 2.3 Fragments of Glass Canes.
Beck Collection of Beads, CUMAA (32.385).
Photograph is author's own.

Canes, examples of which are illustrated in Figure 2.3, could be formed by drawing glass out from a viscous pool or gob and allowing the air to cool it. Examples of twisted canes incorporating two or more colours of glass are also known, and are occasionally encountered in vessel rims, but the majority of LBA canes in Egypt are monochrome, reflecting the usual practice of applying a single colour of glass at a time. Stern (1998, 184) suggests that rods and canes known from Amarna were 'probably not the remains of glassworking, but a commercial form of raw glass'. It is certainly feasible that glass was traded in this form, and it should be noted that the presence of glass canes on a site may thus indicate primary production rather than working, but this does not preclude the utility of canes in glassworking itself: modern day bead makers (including lamp workers) still obtain glass in such canes, the form of which is convenient for re-melting and winding[7].

Ingots

That glass was traded in the form of ingots is confirmed by their discovery at a number of sites. Finds of ingots or ingot fragments include 13 of blue and turquoise glass at Tell Brak (Oates et al. 1997, 85 - 86); 175 of dark and light blue, turquoise and 'lavender' (light purple) at Ulu Burun (Pulak 1998, 202); 1 of red glass at Qantir (Rehren et al. 1998, 227); and one at Amarna. The latter is illustrated in Figure 2.4.

A number of glass making or glass melting crucibles, some with traces of coloured glass still adhering to the ceramic, are also attested in the archaeological record. From Amarna are at least thirty eight fragments of cylindrical vessels thought to be crucibles, including

[7] Mike Tillerman, replica bead maker (personal communication). See also Sode (1995b).

two complete profiles (one of these is shown in Figure 2.5), into which – it was discovered – the Ulu Burun ingots fitted 'as perfectly as possible' (Nicholson et al. 1997, 147). Crucible fragments from Qantir were found to differ slightly in internal diameter to those from Amarna, which is consistent with the slightly different size and shape of the ingot of red glass recovered from that site (see Rehren et al. 2001) though, given the difference in date between Amarna and Ulu Burun (mid 14th century B.C.) and Qantir (13th century B.C.) it is not entirely clear whether the difference in size of the ingots is related to colour or not.

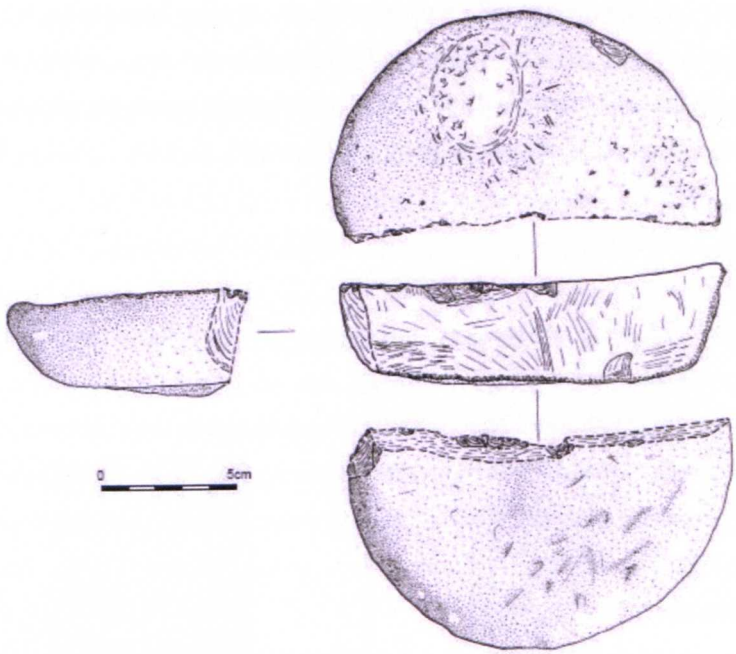

Figure 2.4 Fragment of a Glass Ingot.
From Amarna. Garstang Museum E5654.
From Nicholson (2007, 24).

Figure 2.5 Fragment of a Cylindrical Vessel.
Thought to be from a crucible for the formation or colouring of glass. Surface find from the Palace Dumps at Amarna.
From Nicholson (2007, 91).

Architectural Elements and Inlay

Inlay is most commonly associated with items of furniture or architectural elements. Glass inlay was used in the same way as that of precious stone, and was often prepared by cold-working in an analogous manner, though it could also be mould formed. Inlays were frequently produced in a particular design (such as the shaft of papyrus columns, or specific human or animal body parts) and were often intended for ultimate combination with a range of other materials.

Individual parts of an inlay are usually monochrome, as they are intended to be combined with a number of separate coloured segments. Exceptions to this are generally from those areas which merit more attention to detail. An example of this is an inlay face of the XIX Dynasty, which was moulded in opaque turquoise glass with dark blue glass outlining the eye itself (BM 16375).

Vessels

Although some earlier glass vessels were cold-worked, as noted above, most glass vessels or vessel fragments known from the Late Bronze Age are thought to have been produced using the core-forming technique. They were used as cosmetic or unguent containers[8], and are typically between c.7 and 12cm in height. Monochrome vessels are not rare, but of those made by core-forming, the majority display decoration formed by the application (trailing) of glass. The basic production process is illustrated in Figure 2.6, and an example of a complete vessel in Figure 2.7.

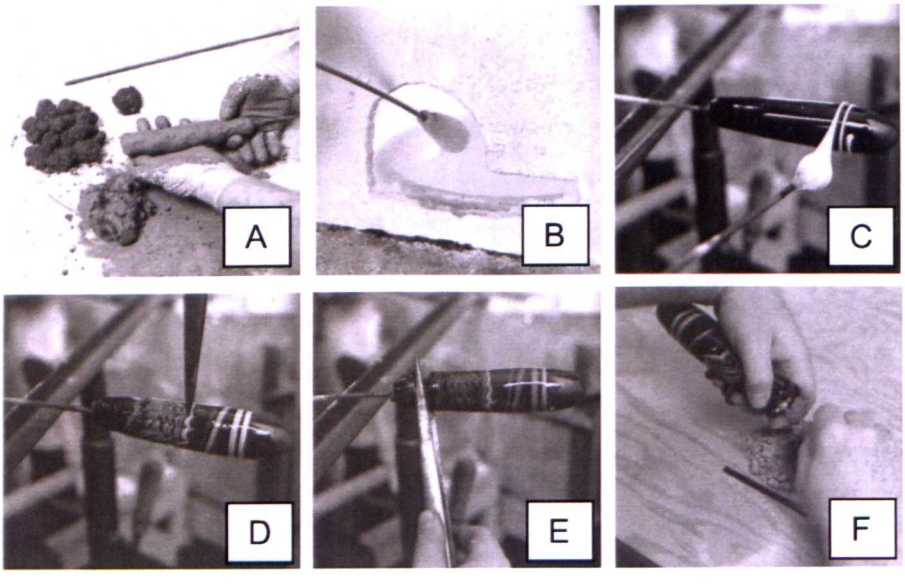

Figure 2.6 The Core-Forming Process.
Modern reconstruction based on a technique thought to have been employed from the 16th to the 1st centuries B.C. The stages shown (A - F) are described in the text. Adapted from Tait (1991, 214 – 215).

[8] Cooney (1976, 141) also suggests that some of the larger examples may have been used as tableware.

The following description of the core-forming process is intended as an accompaniment to Figure 2.6, images A – F (adapted from Tait 1991, 214 – 215)[9]. As shown in image [A], a core of clay and (in this instance) horse dung was shaped around a long metal rod (known as a *mandril*), heated to avoid thermal shock and inserted into a crucible in the furnace through a glory hole (an opening in the furnace wall). Here, it was immersed in molten glass and gently lifted, allowing excess glass to drip back into the crucible before removal from the furnace (see image [B])[10]. The trailed decoration could now be applied: a gob of glass or a glass cane was heated until soft and wound around the continuously turning vessel while being gently pulled in order to form a thin, trailed thread as shown in image [C]. The trails formed by the thread could now be combed or otherwise manipulated in order to produce zigzag or feather patterns (see image [D]). It was common to apply at least two contrasting colours to the base glass colour, as discussed in Chapter 4. Once the initial trails had been applied the vessel may have been marvered (rolled across a flat surface) in order to ensure that the surface of the glass is smooth. The final stages involved manipulating or adding rim, base, and any handles, as is shown in image [E], as well as any additional trails of glass used to decorate these applied parts. Once the vessel had been annealed and cooled, the clay-based core material could be scraped out (see image [F]).

Figure 2.7 Core-Formed Glass Vessel of the XVIII Dynasty.
Two-handled wide necked jar, 8.7cm in height. Blue body with trailed white, yellow and turquoise (opaque) chevrons on neck and festoons on body. Find spot is Memphis.
© Trustees of the British Museum.

[9] The interested reader is also referred to the Corning Museum of Glass's online resource, which includes a number of videos showing the core-forming process and other ancient glass working techniques. This can be found at www.cmog.org.

[10] An alternative, though as yet unsubstantiated, suggestion is that until the first millennium B.C. vessel bodies were formed by applying crushed glass to the core, and heating this within a sealed furnace in a continuation of the tradition of coating faience bodies, and – in Western Asia – glazing (see Stern and Schlick-Nolte 1994, 28 – 29).

Although fragments are more usually recovered, glass vessels were also placed into tombs: thus complete vessels, such as that shown in Figure 2.7, are relatively well represented (though significantly fewer are well provenanced). Nolte (1968) provides what is still a reasonably comprehensive study of vessel forms of the XVIII Dynasty, and attempts to define various 'workshops' (*Werkreisse*) for glass based on stylistic groupings. Parallels for most forms can be found in faience, stone and even (for the palm column flask form of the Late XVIII and XIX Dynasties) wood (see Goldstein 1979).

Beads

Beads could be mould pressed, cast, drawn and ('wire-') wound. Mould pressing involved pushing a blank of heated glass into a mould, and is thought to have been practiced in Mycenaean glass production. The results of casting often appear similar to those of mould pressing, as a mould is used in both processes, but in this instance the glass was made molten inside the mould. This could be achieved by pouring molten glass into a mould or by filling an open mould with crushed glass and placing this in a furnace (this could also be achieved in a closed mould, but the design would need to account for the loss of volume on fusing of the crushed material). Drawing and wire-winding are related processes: drawn glass canes, discussed above, were heated and wound around mandrils (see above) or wires which were coated with an insulating parting layer, possibly of similar composition to that of the core material of core-formed vessels. The process is similar to that employed by modern day lamp-workers, although heating the glass canes would have been rather more difficult without gas-powered flames. Additional colours, also applied with the use of preformed glass canes or from a gathered gob of glass, could be trailed onto the surface and marvered in (or allowed to sink in through surface tension), applied in blobs to form either flat or relief 'eyes', or allowed to stand out from the body of the bead in relief trails. For further descriptions of the various processes of bead making see Nikita (2003), Kücükerman (1995), Lierke et al (1995) and Beck (1927).

Beads were primarily used for personal adornment and as signifiers of social status but could also possess an amuletic function (Ragai 1986, 76 – 77), and this is not exclusive to LBA Egypt (see Sode 1995a, 55). Beads were certainly extensively worn in XVIII and XIX Dynasty Egypt, and were worn by women and men of low and high status alike. Though beads were ubiquitous, the materials from which they were made varied widely, reflecting the status of the wearer.

Depending on the material from which they were made, then, beads could be an important indicator of palatial affiliations in Egypt, West Asia and the eastern Mediterranean. Threaded necklaces were a common method of displaying beads, but they were also applied to other objects. The tomb of Tutankhamen contained thousands of monochrome and polychrome beads of various materials, on collars, necklaces, pectorals, bracelets, a

pair of sandals and three footstools (Lucas and Harris 1962, 52 - 53). At Nuzi, beads were used as architectural elements and beads of faience and glass were found in vast numbers in Temple A (Starr 1939, 445). Glass was worked into a variety of bead forms in the Mycenaean world, primarily in simple wound or relief forms of dark blue and turquoise (Nikita 2003, 23): working debris and occasionally moulds for glass bead production are encountered in palatial workshops, while finished items are found also in burial contexts and less commonly as scattered finds in settlements (Hughes-Brock 1998, 248 - 262). Beads were also articles of long distance trade (see Ingram 2005). Because most beads are small in size, however, they tend to suffer the effects of weathering and corrosion more heavily than larger objects, though such effects are less severe in the dry Egyptian climate.

Amulets

The range of amulet forms known in LBA Egyptian glass is relatively restricted. Most frequently encountered are the heart amulet, an example of which was sampled in the present study (see Figure 2.8); profile representations of the goddess Thoeris; and the papyrus column, all of which were shaped through hot manipulation and the drawing of canes or rods of glass around a mandril, in an analogous process to that of bead production (see above). Also encountered is the mould-formed *djed*-column sacred to Osiris, and the 'buckle' or girdle of Isis which is invariably found in red glass (Cooney 1976, 1). These forms are relatively consistent from the reign of Amenhotep III to that of Ramesses II.

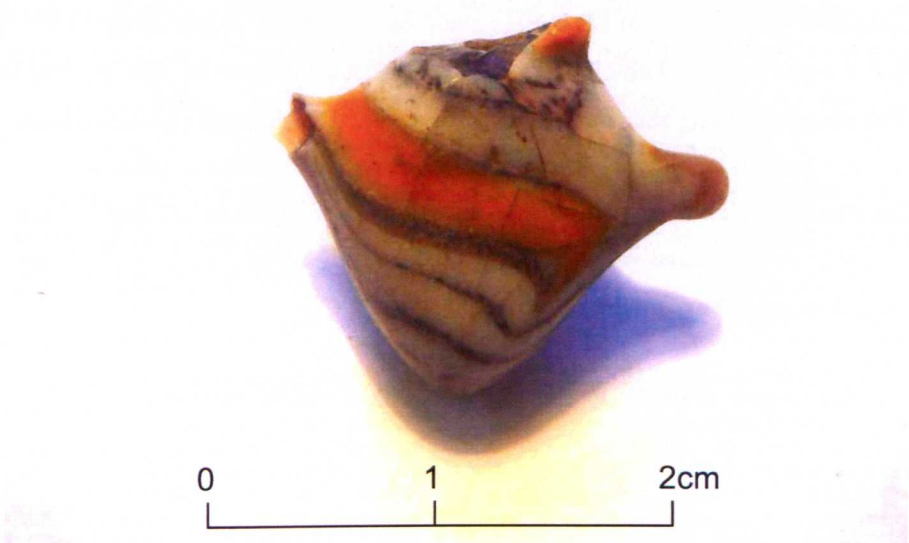

Figure 2.8 Glass Heart Amulet
18th Dynasty heart amulet recovered from Amarna. Purple body with opaque yellow and white applied decoration. Beck Collection of Beads, (MAA 1932.412).
Photograph is author's own.

Other Personal Display and Adornment

Other items frequently encountered in glass include earrings and earplugs, which are usually polychrome. Pendants of glass are also found in a variety of forms, some of which – such as the pomegranate – were representational (see Cooney 1976 for examples).

2.b. The Material Studied

> "...many difficulties would disappear under the microscope, which revealed differences in material invisible to the naked eye."
>
> Horace C. Beck

The sampling strategy employed is outlined below. This is followed by some details of the Beck Collection of Beads housed at Cambridge University Museum of Archaeology and Anthropology (CUMAA / MAA), from which the majority of samples were taken, and a brief explanation of the methods used to divide and label the samples. A separate section on the sampling strategy for ToF-SIMS is then presented, as this technique focuses on a slightly different set of questions to those using EPMA. Following this is a note on the terminology used to describe colour employed in the present study. Two lists of relevant sites are presented: the first is of those sites from which material was obtained for the present study; the second is a list of other sites which are of relevance to the arguments and discussions presented in the main body of the work. Full catalogue details for all samples can be found in Appendix 1. Working photographs of the items sampled from CUMAA are provided in Appendix 3.

Sampling Strategy

The main aims of sampling were to provide a broad basis upon which research into the colouring and opacification of LBA glass could be analytically examined by EPMA, and to provide a platform for ToF-SIMS analysis of a selected number of samples. The focus was thus on the sampling and analysis of samples from the full range of colour groups (see below), but in particular samples of lead antimonate and calcium antimonate opacified glasses. The Beck Collection was used because of its large selection of Egyptian material, most notably from Amarna which was occupied for only a limited time and the material from which can thus be relatively firmly dated.

It was also hoped to develop a basis for comparison between the manufacturing technology and raw ingredients of the glasses from different regions (Egypt, Mesopotamia, the Levant and Anatolia). The initial aim was to obtain samples from excavations in Turkey, Syria and Jordan against which the analysis of Egyptian glass from the Beck Collection could be compared. Problems encountered in obtaining samples have unfortunately meant that only a very small proportion were eventually sourced from primary excavations (three from Tell Bazi in Syria and four from Deir 'Ain 'Abata in Jordan). With this in mind, it was decided to extend the criteria for selecting samples from the Beck Collection in order to provide a wider chronological context in which to place the results for well provenanced LBA glass: some samples from the 1st millennium B.C. have thus been included, from Italy, Greece, Egypt and Mesopotamia. To date, there have not been many chemical analyses of glasses dating to the first half of the first millennium

B.C. (though with some notable exceptions: Arletti et al. 2009; Freestone 2000; Freestone 1992; Henderson 1988a; Henderson 1988b; Henderson 1985), and it is hoped that the results presented here can add to the growing body of knowledge on this period of glass production as well as providing a more complete backdrop against which the analysis of LBA glass can be discussed.

The Beck Collection of Beads

As noted above, the majority of samples were taken from the Beck Collection of Beads. Now associated with the Bead Study Trust, it was left to CUMAA by Horace C. Beck, who personally amassed the majority of the collection from the late nineteenth century until his death in 1941: it was re-housed here after the end of the Second World War. The collection consists of beads and small items made from a vast range of organic and inorganic materials, prehistoric to twentieth century in date.

Many of the items in the collection were gifted to Beck by excavators who had asked him to report on their findings. Others were obtained from less secure sources such as sales, or were given to him by travellers and explorers. Thankfully, the details of acquisition are well recorded for most of the collection and the dates of acquisition are often coincident with those of the excavations (as at Amarna and Ur) from which they were obtained.

A full listing of Beck's own publications is too long to report here, but may be found in the Bead Study Trust's *Catalogue of the Beck Collection*, published in 1997. Of particular note is the monograph *Classification and Nomenclature of Beads and Pendants* (Beck 1927), from which a consistent terminology for beads has been drawn in subsequent studies. A large part of the collection was catalogued in 1984 by Julian Henderson, Helen Hughes-Brock, Dan Barag, Leo Biek and M. Guido (only some of which was included in the 1997 publication).

The Beck Collection: Division of the Data

In total, samples were taken from 36 listed 'items'[11] in the museum collection. Some of the single catalogue listings include a large number of separate pieces, so that in total 89 individual fragments and small objects (beads, amulets, canes, etc.) were sampled. The total number of samples taken and analysed from the collection thus amounts to 116. A further 7 samples, from Tell Bazi and Deir 'Ain 'Abata, can be added to this list.

Each sample thus constitutes a single piece of glass of a single colour. Where one museum item contains two or more sampled colours, these were counted as separate samples and

[11] The catalogued item numbers in the museum collection refer to dates of acquisition, source and provenance, so that a number of separate beads or amulets, for example, may be given a single item number, which has often been further sub-divided for clarification purposes.

can consequently be distinguished in their labelling. This is logically justified by the need to identify separate colours of glass in the present study, and by the possibility that coloured glasses made in different primary locations were added together in the formation of a single object. The tables given in Appendix 1 are divided by item numbers (such as 32.385) taken from the museum accession / catalogue code, and additional letters or numerals used to distinguish between items or the colours present on a single item (for example, 32.385IV and 32.385V). The museum item numbers provide a convenient grouping as all samples with a single code are from the same site or find location, and the same date. Added to this are broader distinctions such as date category or regional provenance.

Samples for ToF-SIMS

Sample acquisition for ToF-SIMS analysis was less problematic, as it was possible to use the technique to analyse existing samples which have already been examined by other techniques, or had been earmarked for such. Of fourteen samples selected for potential ToF-SIMS analysis, six samples from Amarna were taken from amongst the material from the Beck Collection analysed by EPMA, the results of which are presented in Chapter 5; five samples from Tell Brak were included among those published in Henderson (1997, 94 - 100); and data for three samples from Mycenaean Thebes is currently being analysed and prepared for publication by Kalliopi Nikita of the University of Nottingham. The samples were deliberately selected to represent glass from the three major areas involved in its production and / or working (Greece, Egypt and Western Asia) as well as those coloured and opacified by both calcium and lead antimonate, forming a basis for comparison between regions and between the methods of colouring and opacifying white, yellow and turquoise glasses.

Developing the use of a technique so new to archaeometric research presented its own difficulties, however, and an initial group of samples which were collected for analysis could not be used due to an unforeseen problem with the type of resin in which they were mounted (see Chapter 6). The analysis was ultimately highly successful, as I hope is demonstrated in Chapter 6, but the delays encountered (particularly with sourcing and obtaining suitable resin and a new sample set) meant that only four samples of those mentioned above could eventually be analysed with the technique (for details of these see Appendix 1).

In order to maximise the amount of information retrieved it was thus decided that selecting two samples of lead antimonate and two of calcium antimonate opacified glass would provide the strongest basis for comparison. These constitute one sample each from Amarna and Tell Brak, and two from Mycenaean Thebes (one of which was from a vessel fragment stylistically consistent with Egyptian imports to Greece).

A Note on Colour Assignations

One of the central themes of this work is that of colour, and descriptions or assignations of glass colour are thus frequently made, most prominently with reference to the production technology of glass (Chapter 3), the relative abundance of various colours of glass in finished items (Chapter 4), and to the grouping of analysed samples (Chapters 5 and 6).

It is important, of course, to maintain consistency when describing colour. Standardised markers of colour variation such as the Munsell colour chart, however, have not been used. There are a number of interrelated reasons for this. One is the diversity of the evidence: some colour assignations are derived from the primary material (such as the Beck Collection) whereas others are derived from catalogues or are discussed with relation to the published results of analytical studies, which preclude a unified method of classification: some publications (see for example Hayes 1975; Brill 1999a) provide detailed descriptions of the colour assignations used, but these are not always present and there is no way of guaranteeing consistency between publications. The second reason is tied in with the first, and thankfully resolves most of the problems which might arise from the use of diverse sources of evidence: there exists a fairly compartmentalised range of colours for glass of the Late Bronze Age, a fact which is in part based on production technology (though the arguments presented in Chapters 4 and 7 indicate additional reasons for this). Finally, aside from their subjectivity (see Chapter 3), colour charts are notoriously difficult to use when dealing with glass: even opaque samples often allow a degree of light transmittance so that the thickness of the piece examined affects the colour viewed.

In most instances the assignation of colour was thus fairly simple. As noted above the range of colours produced tended to be fairly compartmentalised so that red, yellow, white, turquoise and purple glasses tend to show only minor variation in hue at this time. Turquoise is used here to refer to opaque glass only, which is nominally a blue-green colour, but which has also been used in a number of catalogues to describe glass which might be more appropriately termed 'opaque light blue'. Generally speaking, however, the same range of hues which are described as turquoise for ancient glass are those also seen in the mineral itself, at least so far as it was used in Late Bronze Age Egypt and Mesopotamia. Although green glass is found in a wider range of hues than red or yellow, for example (a direct result of the more restricted manufacturing technology required for the production of red glass), it does seem to form a distinct category and is therefore easy to assign. Blue glass is perhaps the most difficult to categorise, largely because there is no particular accepted 'cut off' point between light and medium, or dark blue. Where it was encountered in museum catalogues the description given was thus adhered to (photographs were used only to determine the relative abundance of various colours) and where the primary material was described, the terms 'light' or 'dark' were only used in exceptional

cases. Because the darkest blues are almost invariably coloured by cobalt and are far darker than the colours which can be achieved with a copper colorant alone (see Chapter 3) their distinction was fairly straightforward. Light blue, as noted above, is usually opaque and the distinction between this category and 'turquoise' is not clearly defined, nor necessarily archaeologically, linguistically or historically relevant (see Chapter 4).

Sites from which Samples Originated

An outline of the sites from which material sampled here originated is given below. The importance of Amarna both in the number of samples taken from this site and in its central place in many of the other arguments and discussions presented in the main body of this thesis means that more attention is necessarily paid to the description of this site.

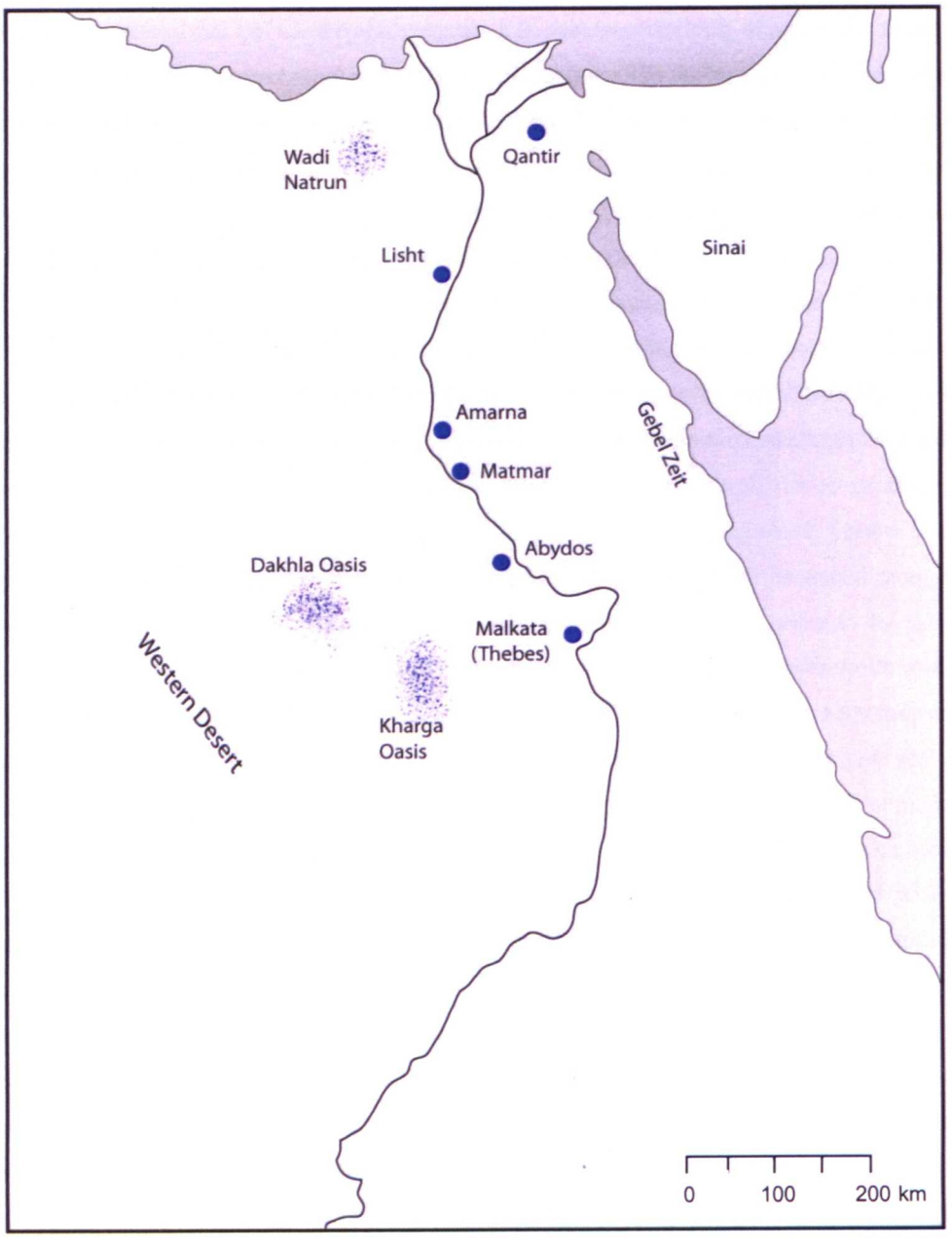

Figure 2.9 Egyptian Sites and Locations Mentioned in the Text.

Amarna, Egypt

The location of Egyptian sites discussed in the text (both those from which material was sampled and others of relevance, discussed below) can be seen in Figure 2.9. Amarna (in some publications referred to as Tell el-Amarna) is the modern name for the site of Akhetaten, the capital of Akhenaten (Amenhotep IV). The layout of the site, situated in Middle Egypt, can be seen in Figure 2.10.

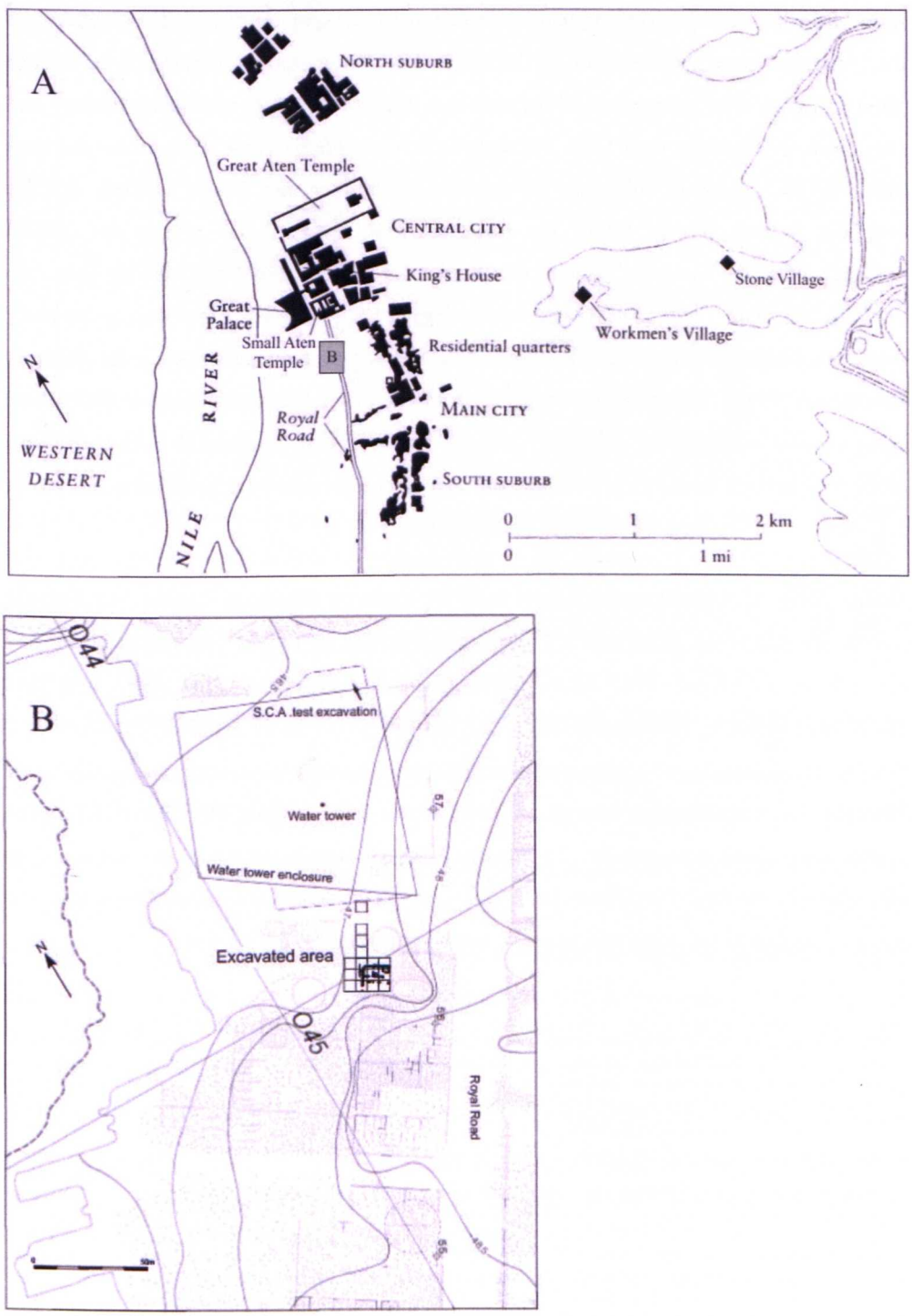

Figure 2.10 Principle Areas of the City of Akhetaten, Amarna.
The location of site 045.1 (**B**), excavated intermittently from 1993 to 2003 by the Egypt Exploration Society, in relation to the principle monuments of Amarna (**A**). From Nicholson (2007, 28).

At its height, the city of Akhetaten may have had a population of up to 50,000 (Kemp 1989, 269). The main period of occupation was from c. 1346 – 1330 B.C. after which it was abandoned when the royal court moved to Memphis during the reign of Tutankhamen. The site was not reoccupied, so that material recovered from stratified contexts can be firmly dated to the mid 14th century B.C.

Aside from the well-known corpus of international correspondence usually referred to as the 'Amarna letters' (see Chapter 4), the site yields a large amount of some of the earliest glass in Egypt. The excavation of Amarna was begun in the late nineteenth century and continued, with breaks, until 1936. Flinders Petrie excavated various areas of the site from 1891 – 1892, those of relevance to this study including the Palace Dumps, and the Northern Suburb (Petrie 1894). He suggested that several areas of the site offered evidence of glass 'factories' though the precise location of these was not recorded (see Nicholson 1995b, 125). Excavations by the Egypt Exploration Society during the early twentieth century focused on the central city and residential quarters (see for example Pendlebury 1951). The material sampled from the Beck Collection derives from these early excavations and was gifted to CUMAA by the Egypt Exploration Society (though some of it derives from Petrie's campaign): references to dates of acquisition and – where recorded – find location are included in Appendix 1.

Investigation of Amarna was resumed in 1979, again by the Egypt Exploration Society; first at the site of the Workmen's Village and followed by further excavation of the city (see Kemp 1979; Kemp 1987; Kemp 1989). The most recent excavation, directed by Paul Nicholson, began in 1993 at site 045.1, the location of which is indicated in Figure 2.10 (B). Petrie, in his original excavations, had labelled this area as the location of a number of 'moulds'. A magnetometer survey of revealed the area to yield significant anomalies, higher than those obtained for the pottery kilns or bread-making ovens known from elsewhere in the city (Nicholson 1997, 50). The area selected for excavation was a low mound, sloping to the north and west and with a gentler slope on the east.

Excavation of site 045.1 revealed several graves, which may predate the establishment of Amarna or may be burials of the first workmen brought to the site, though disturbance rendered to these by the overlying industrial features makes the latter an unlikely scenario (Nicholson 2007, 31). The main industrial phase appears to be short-lived, and includes kilns associated with faience objects, faience moulds and pottery. A number of fragments of glass were also present (Nicholson 1995a, 15 - 16). Nicholson (2007, 31) suggests that the production of these materials was primarily related to the construction of the palace and temple, and was moved further away once these activities were completed. Walls were constructed over the kilns, so it is clear that the industrial phase was over before the abandonment of the site.

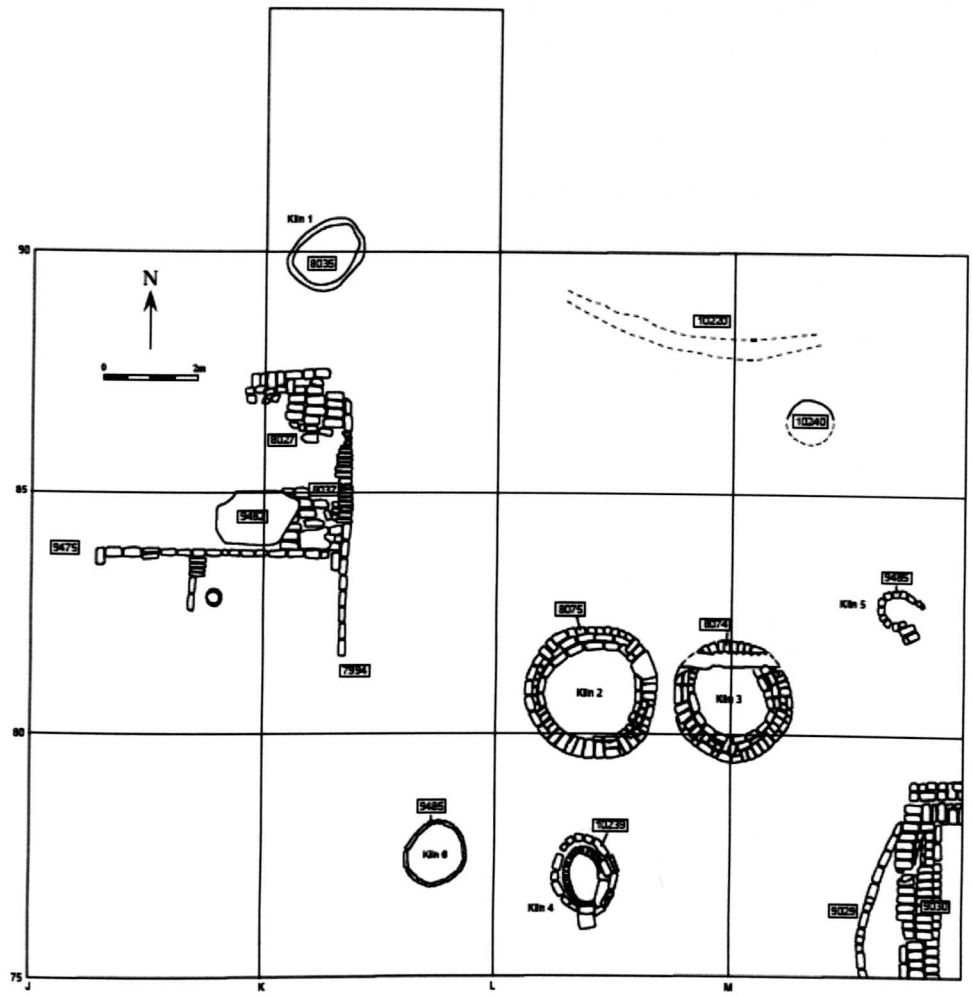

Figure 2.11 Excavated area of site 045.1, Amarna
Corresponding to the area outlined in Figure 2.10 (B). The main industrial phase is shown here. Kilns 2 and 3 are larger and have far thicker walls than the surrounding kilns, thought to be associated with a potter's workshop.
From Nicholson (2007, 31).

Some glass was found adhering to crucible walls (Nicholson 1997, 52), and of particular significance were 'Kilns'[12] 2 and 3, the location and plan of which are illustrated in Figures 2.11 and 2.12. Both kilns showed evidence of vitrification due to high temperatures, more pronounced in Kiln 3, which also retains elements of what has been interpreted as a 'sacrificial render' of clay and lime, used to protect the kiln walls from vitrification. Kilns 2 and 3 were larger than the surrounding structures, one of which (Kiln 5) was interpreted as little more than a hearth. Similarly, their walls were thicker (at 0.5m) than those of the other kilns, and were built using a more complex pattern of brickwork which appears to be designed to provide maximum resistance to thermal shock and maximum retention of heat (see Nicholson 2007, 38 – 44). The positioning of the vitreous material also suggests the original presence of several shelf-like structures in the better preserved Kiln 3, and at least one of these seems to have been placed in front of an

[12] I follow Nicholson (2007, 34) in referring to these as 'kilns', though he suggests that they might be more appropriately termed furnaces.

opening in the (almost certainly domed) superstructure where the vitreous material extends into the kiln wall (Nicholson 2007, 40).

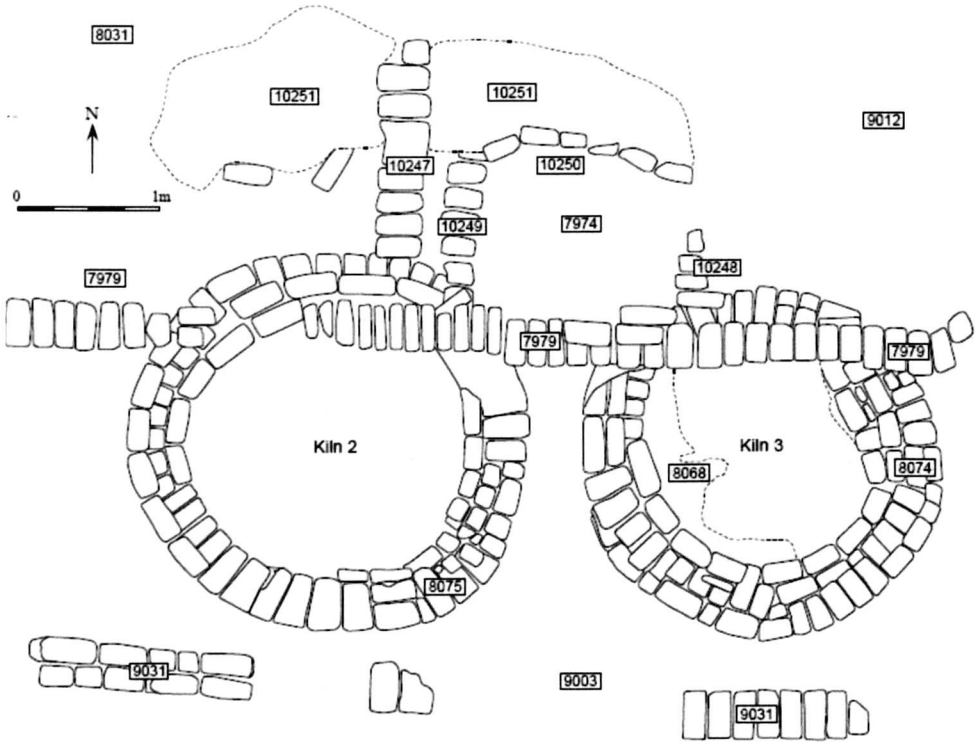

Figure 2.12 Plan of Kilns 2 and 3 from Site 045.1, Amarna
Kiln 3 contains partially vitrified material and the remains of a sacrificial render. The straight walls running east –west are from a later phase of building.
From Nicholson (2007, 38).

That glass was melted in these kilns is apparent, but it is still debatable whether primary glass production occurred at the site. Some lumps of 'frit' have been identified (Nicholson 1997, 52), though Shortland (2000c) suggests they were used in the production of faience, not glass. If primary glass production was occurring at the site, it might be expected that larger quantities of frit would be recovered. As noted previously, however, Jackson et al. (1998) have demonstrated that the primary production of glass is possible without the fritting stage in a furnace based on the design of the Amarna kilns. Petrie himself, though he advocated the fritting process elsewhere, noted that surface of a 'block' of glass (now lost) from an unnamed location at the site was 'frothy and worthless', a result of the burning off of carbonic acid during primary production: had fritting occurred, we might expect the ground products of this, when introduced to high temperature for glass production, to have produced a smoother ingot (Petrie 1894, 26; Nicholson 2007, 17). It might thus be stated that although the evidence remains inconclusive at the present time, there is no reason to suppose that primary production was not occurring at Amarna. It is argued later in the present work that primary glass production may have been located

away from other craft areas, however, so if it were occurring at Amarna, we may be looking in the wrong place at site 045.1[13].

Menshiyeh / Abydos, Egypt

It has been suggested that Menshiyeh, in close proximity to Abydos, was a site of glass working and it was assigned by Newberry (1920) to have been used for such between the 13th and 12th centuries B.C. Keller (1983, 20) has expressed doubts about this, based on the lack of material from the site itself and a re-examination of Newberry's original notes but Stern and Schlick-Nolte (1994, 26 – 27) support Newberry's suggestions, noting that he collected 'slag' and coloured glass canes from the site. In any case, the appearance on the Egyptian art market in the first part of the twentieth century of numerous fragments said to have come from the site may obscure the genuine provenance of some of them. What is apparent, at least from a typological perspective, is that the glass said to come from this site fits into the general corpus of LBA Egyptian material.

Tell Brak, Syria

The location of Mesopotamian and Western Asian sites mentioned in the text (both those from which material was sampled and others of relevance, discussed below) can be seen in Figure 2.13. Tell Brak is located in northern Syria, and lay within the heartland of the Mitanni Empire. The main tell covers an area of over 40ha and is one of the largest in northern Mesopotamia (Oates et al. 1997, xvii). Of relevance to glass studies is the second millennium B.C. Hurrian city, located on the northern side of the tell.

The majority of glass finds from the most recent series of excavations at Tell Brak were in levels dating to between c. 1500 – 1200 B.C. (Oates et al. 1997, 81). Henderson (1997, 95) suggests that most of the material may be more precisely dated to the 14th century B.C. and the sample taken for the present study is from a piece dated to c.1300 B.C., though there are also some glass fragments from contexts dating to the 15th century B.C. Glass reported from the site was largely found in the rooms and courtyard of the palace. A total of 127 beads (for which blue and white were the most common colours), a variety of plain moulded plaques, pendants and gaming pieces, a fragmentary glass cylinder seal and some elements of what may have been architectural inlay were found (for a more complete discussion of these items see McDonald 1997, 101 – 103; Oates et al. 1997, 86).

A total of 13 ingots and fragments were also recovered from the Mitanni palace at Tell Brak, the best preserved of which came from the doorway between Room 5 and Room 7

[13] After the time of submitting this thesis for examination, an article was published by Smirniou and Rehren (2011) in which the authors contest that more evidence of primary glass production has been recovered from Amarna than had previously been accounted for. They re-examined the material from Petrie's original excavations of the site, and note the discovery of what is described as a semi-finished glass, containing lumps of quartzite and newly formed lime-rich crystal phases.

(see Oates et al. 1997, 85). The most completely preserved ingot fragments reveal an approximate diameter of 15cm and most were of light blue (or 'turquoise') opaque blue glass. A volume of 'cullet' was also found at the site in the same colours as the ingots (Oates et al. 1997, 86), and may thus be better termed 'working debris', as it is more likely to be from broken ingots than finished items.

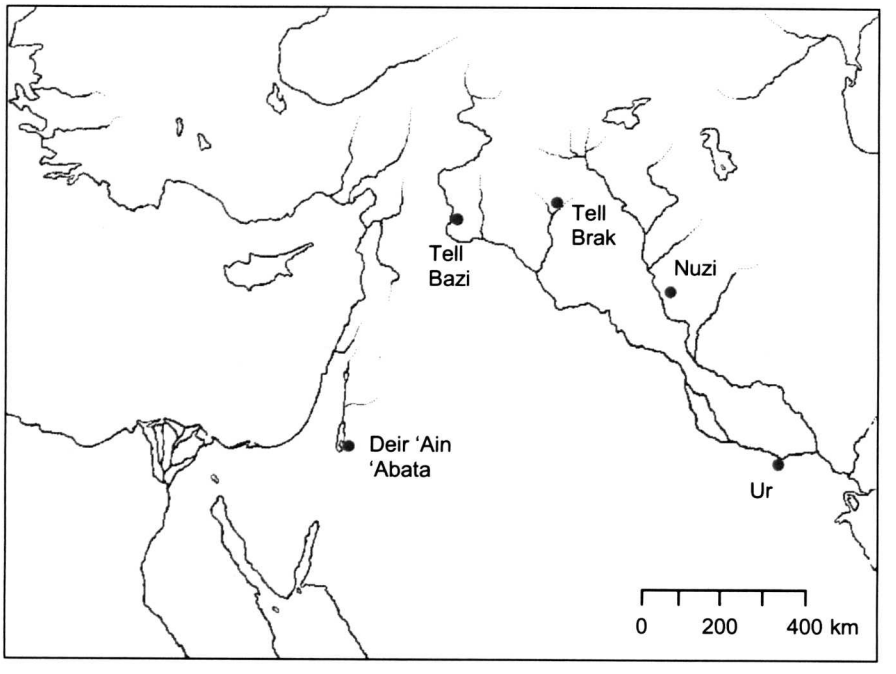

Figure 2.13 Mesopotamian and West Asian Sites Mentioned in the Text.

Tell Bazi, Syria

Tell Bazi is located in northern Syria, approximately 60km south of the modern border with Turkey. The site lies on the eastern bank of the Euphrates. Its ancient name is unknown, but it was a part of the Mitanni empire from the 15th to the 14th centuries B.C. when it fell under Hittite rule. The site consists of a citadel and a lower city, and occupation levels come to an abrupt end in the early 12th century B.C., though a Roman fortress was later established there.

Due to the damming of the river to create the Tishrin Lake in 1999, rescue excavations – from which the material sampled for the present study was retrieved – have been conducted by the Deutsches Archäologisches Institut under the direction of Adelheid Otto and Berthold Einwag (interim reports are published in Olmo Lete and Molterno Fenellós 1999).

Deir 'Ain 'Abata, Jordan

Deir 'Ain 'Abata (also Dayr 'Ayn 'Abata and meaning 'monastery at the Abata spring') is situated on a steep mountain slope overlooking the modern town of Safi, at the southeastern end of the Dead Sea. It was a burial site from ca. 3000 B.C. to the mid

second millennium B.C. Occupation levels date from the 1st century B.C. to the 9th century A.D., and at the centre of the site is a Byzantine monastic complex built around a natural cave which held religious significance for early Christians. Systematic survey and excavation – from which the material sampled for the present study was provided – was conducted by K. D. Politis with the support of the British Museum from 1987 to 1996 and is being prepared for publication (Politis, in press) at the time of writing.

Ur, Iraq

The glass from the cemeteries at Ur, Babylonia which was sampled in the present study was retrieved from the excavations conducted by Leonard Woolley in the 1920s and 1930s (see Woolley 1939). The glasses were stated as coming from the 'Kassite period' but the majority have since been more finely dated on typological grounds. Dan Barag has examined some of the material at CUMAA, and the dating of the majority of items is correspondent with that of the vessels from the Ur cemeteries found in other collections (listed by Barag 1970, 156 - 159), though the samples listed in the museum catalogue as 'from the time of Nebuchadnezzar' (item 47.2133) can more precisely dated to the late 6th or early 5th centuries B.C. (see Barag 1970, 147).

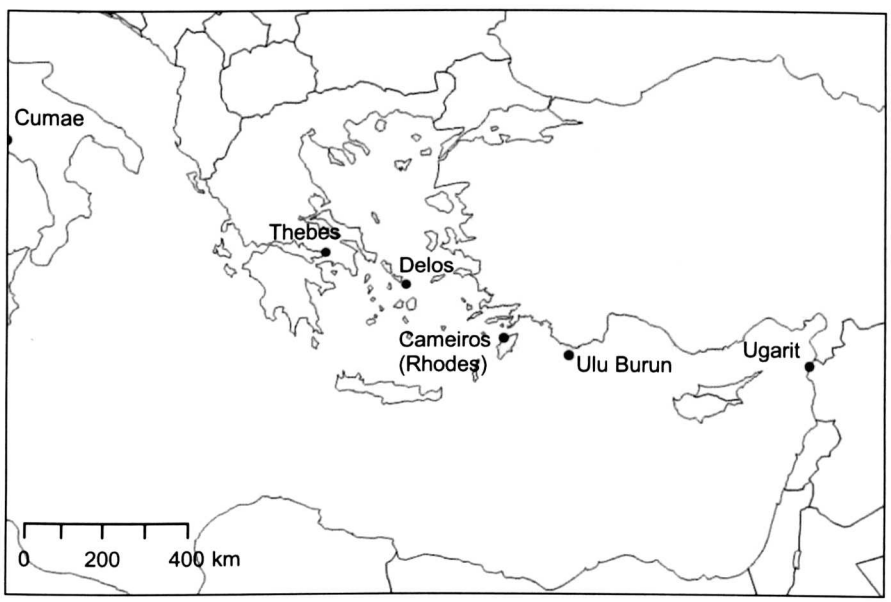

Figure 2.14 Mediterranean Sites Mentioned in the Text.

Thebes, Boeotia, Greece

The location of Mediterranean sites mentioned in the text (both those from which material was sampled and others of relevance, discussed below) can be seen in Figure 2.14. Thebes, Boeotia, was a major Mycenaean centre. Rooms N and X in the 'House of Kadmos', a sizeable building in the centre of Thebes, were identified as the location of jewellery workshops (Nikita 2003, 28) and contained, among other materials, hundreds of glass beads dated to approximately 1190 B.C., when the building was destroyed by fire

(Nikita and Henderson 2006, 77). The glass sampled in the present study was taken from comparable items at the cemetery at Megalo Kastelli and Gymnasio Tomb 23 and is well dated (LH IIIB) by association with other material.

Other Sites of Relevance

Aside from the sites outlined above, a number of others should be mentioned as the evidence they yield is relevant to the arguments and discussions presented in the main body of the thesis. The location of these sites is also illustrated in Figures 2.8, 2.12 and 2.13, above.

Malkata, Egypt

Malkata is the site of the Theban royal residential complex founded by Amenhotep III, and as such provides direct precedents to the glass remains from Amarna. It is located just south of the later mortuary temple of Ramesses III on the west bank at Thebes.

Excavations at the site were conducted by the Metropolitan Museum of Art (MMA) from 1910 to 1921, though the site remains unpublished (Keller 1983). Fragments of glass vessels, amulets and other objects were found throughout the site including the main palatial residences, the Temple of Amun and the storage magazines. Remains associated with glass working were identified among the craft quarters to the south of the main palace complex, but another site of possible glass working was located in the centre of the palace complex. Little of this material was conserved, however, and Keller has identified 'only some three dozen glass rods and a few test droplets of glass and glass waste' in the MMA collection (Keller 1983, 20 - 21). Far more abundant, however, are the fragments of glass vessels, inlay and jewellery, which have been used – along with material from Amarna – as the basis of Nolte's (1968) classification of early glass in Egypt: particularly characteristic of glass from Malkata, according to Nolte, is a medium blue-green body colour for vessels.

Qantir, Egypt

Qantir, in the northeastern Nile Delta, was the site of an industrial estate created in order to serve the building works at nearby Pi-Ramesses, the capital of Ramesses II (1290 – 1224 B.C.). The most extensive industrial feature at Qantir is a large bronze-casting factory, but recent excavations have revealed that this is accompanied by a number of works for smaller scale high temperature production, perhaps centred around the use of copper.

Rehren and Pusch (1997, 127) date the glass and associated finds (stratum B/2) from the site to, or just prior to, the reign of Ramesses II. Included among these remains are at least 40 large crucible fragments (and several hundred smaller ones), many with traces of red

glass adhering to them and the remains of a lime parting layer (Rehren and Pusch 2005, 1756); layered slag; remains of uncoloured glass; and a complete ingot of red glass coloured by Cu_2O (Rehren et al. 1998, 227). The size of the crucibles was standardised and their interior dimensions match that of the ingot from the site, though the complete ingot only fills about three quarters the height of the surviving complete vessel wall (Rehren and Pusch 1997, 132 - 137). Of particular interest is a substantially preserved crucible filled with a heavily corroded block of raw glass, containing abundant quartz grains. Some of these are relatively large and rounded sand grains but they are mixed with large quantities of highly angular, very fine quartz dust (Rehren and Pusch 2005, 1756). Due to the difference in remains from those at Amarna, it has been suggested that the processes of glass production were different at the two sites (see Jackson 2005, 1751), though as noted above it is by no means certain that primary glass production occurred at Amarna. No remains of secondary glass production – that is, working of glass into objects – have been found at Qantir, and only a few isolated fragments of blue glass have been found in addition to the red glass which dominates at the site (Rehren and Pusch 1997, 136).

Lisht, Egypt

Lisht is the name of the modern village situated close to the pyramid complex of Amenmhat I, where a settlement was established and occupied from the Middle Kingdom to the Third Intermediate Period.

Excavations were conducted at the site by the MMA from 1906 to the mid 1930s, primarily focusing on the houses to the north and east of the pyramid. A large number of faience and glass objects were recovered, including fragments of glass inlay, beads, and over 184 fragments of core-formed, decorated glass vessels (El Goresy et al. 1997, 471). A house at the northern side of the pyramid was identified as a faience and glass workshop, and finds from here included crucible fragments with adhering glass, lumps of coloured glass including an irregular lump of blue glass weighing 4.2kg (see Schlick-Nolte and Leirke 2002, 18), glass rods and a vitrified material described as 'slag'.

Keller (1983, 24 – 25) notes some difficulty with dating the glass from Lisht, largely due to the scattered nature of remains at the site, but notes that it must fall within the second half of the New Kingdom, with the very earliest dates coming from scarabs of Sety I (1306 – 1290 B.C.), though the majority of the material is thought to be somewhat later still. This material is thus later than that from the palace sites of Malkata and Amarna, which provide the other main evidence of glass working in New Kingdom Egypt, and much of it may be later than Qantir. In any case, glasses and artefacts from Lisht are markedly (visually) different to those of earlier workshops at Malkata and Amarna, as noted by Nolte (1968). Keller (1983, 26) notes that, by comparison with that from

Malkata, glass from Lisht contains more air bubbles and other inclusions, exhibits 'tinged' colours, and is less expertly worked (thicker vessel walls, simpler trail decoration and minimal applied elements). The typical colour range from Lisht includes copper blues (but not the darker, cobalt blues), dark purples, brown, and a higher proportion of green, white and yellow than is known from Malkata and Amarna.

Nuzi, Iraq

The Hurrian site of Nuzi is located on the mound of Yorgan Tepe, situated 13km southeast of the town of Kirkuk in modern Iraq, approximately 130km from the River Tigris. The site was excavated from 1925 – 1931 by the American School of Oriental Research in Baghdad, the Iraqi Department of Antiquities, and Harvard University under the direction of Richard Starr. The majority of glass from the site comes from Stratum II, thought to date to between c.1440 and 1340 B.C.

Approximately 11,000 glass beads were recovered from the temple complex, along with small fragments of approximately 40 core-formed vessels and smaller numbers of other glass objects including amulets and figurines (Shortland et al. 2008, 217). Starr (1939, 446 – 447) lists beads made using translucent green, black, opaque yellow and opaque white glass. Both monochrome and polychrome beads were found, and forms included eye beads, ribbed beads, barrel beads, disc beads, mosaic beads and cylindrical beads. Decorated glass vessels were found in a range of colours: for those which were not lost to corrosion, Starr (1939, 458 – 459) lists the colours applied to blue or 'bluish-green' vessel bodies in order of frequency: white, yellow, 'orange' (a range of hues including red) and black. No 'true' green glass was found. Barag (1970, 40) has also reported three fragments of a single ingot among the material recovered from the site.

Ulu Burun, Turkey

The remains of a wrecked ship dating to c. 1300 B.C. were discovered at Ulu Burun, approximately 6 miles due south-east of Kas on the Anatolian coast, in 1982 (Bass et al. 1984; Pulak and Frey 1985; Pulak 1998, 188). A series of excavations conducted by the Institute of Nautical Archaeology (INA), Texas, revealed the ship to be carrying a cargo largely comprised of raw materials including 354 copper ingots (317 of which were 'oxhide' shaped), 175 plano-convex glass ingots (most of which were dark blue) and large quantities of pottery, organic materials such as wood, raw ivory, gold and silver jewellery (usable and scrap), and tens of thousands of beads of a number of materials including glass and faience (Ingram 2005, 4; Pulak 1998, 191 - 206). The origin of the ship remains uncertain, but it is thought to have been travelling east to west; that is, the intended destination of the goods on board was probably Mycenaean Greece (Pulak 1998, 218 - 220). The size and form of the ingots provides a direct parallel with moulds recovered from Amarna (see Nicholson et al. 2007). It has also been suggested, on the basis of recent

LA-ICP-MS work on their trace element composition (Jackson and Nicholson 2010), that the Ulu Burun ingots were manufactured in Egypt.

Glass beads were either wire-wound (corresponding to most of the Egyptian beads sampled from the Beck Collection) or relief-beads of the Mycenaean type (see Hughes-Brock 1998). Bi-chrome and polychrome beads can be distinguished among the Ulu Burun assemblage, including eye beads and crumb beads (which are not represented in the Beck Collection for this period), but corrosion has made a clearer definition of the colours impossible (Ingram 2005, 49 - 62).

3. Archaeological and Scientific Approaches to Glass and Colour

3.a. The Science of Glass, Glass Coloration and Opacity

> "A [transparent] glass is structurally a large molecule, containing no internal surfaces or discontinuities having any dimensions approaching the wavelength of visible light. Consequently the light can pass through the glass virtually unhindered."
>
> Roy Newton and Sandra Davison 1996

In the first part of this chapter the current state of knowledge of the chemistry and physics of glass is presented. This is followed by a more specific exploration of work to date on the production of various colours of glass, both opaque and translucent, focusing on the Late Bronze Age, with some consideration of later developments. The second part of the chapter, by contrast, provides an introduction to textual, linguistic and archaeological facets of the subject of colour, and a consideration of the theoretical approaches to this, of relevance to the arguments presented in Chapters 4 and 7 in particular.

The Physics and Chemistry of Glass

The definition of glass as set by the US National Research Council in 1976 is as follows:

> Glass is an x-ray amorphous[14] material which exhibits the glass transition, this being defined as that phenomenon in which a solid amorphous phase exhibits, with increasing temperature, a more or less sudden change in the derivative thermodynamic properties such as heat capacity and thermal expansion coefficient, from crystal-like to liquid-like properties.

The glass transition range is shown in Figure 3.1. It is a range of temperatures over which, on heating, the glass transforms from having solid-like properties to liquid-like properties exhibiting viscous flow. The difference in contraction between a glass and a crystalline material is caused by the viscosity of the glass, which prevents the atoms from arranging themselves in a crystal structure unless very slow rates (specific to the particular composition under question) of cooling are allowed (Shelby 2005, 4 – 5).

[14] X-ray amorphism indicates a lack of long range periodicity (repeated units). Thus the crystalline form of silica (cristobalite) has an X-ray diffraction pattern represented by intensity peaks, a result of the ordered diffraction X-rays undergo within a crystal structure. In contrast, glassy silica results in a smooth, poorly defined 'halo' as X-rays are diffracted more randomly by the amorphous glass.

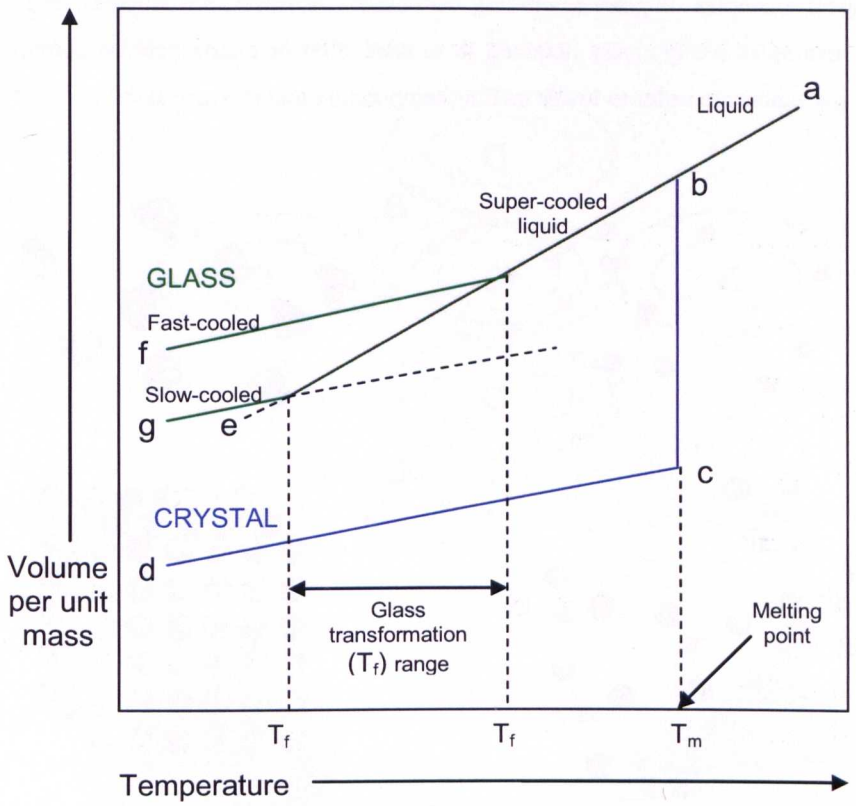

Figure 3.1 Effect of Temperature on the Enthalpy of a Glass Forming Melt.
Enthalpy can be considered equal to volume as the two behave in a similar fashion. After Shelby 2005, 3 – 6.

Under normal (non-glass-forming) conditions a given material would crystallise at point Tm on the diagram, causing a sharp decrease in volume (as the crystalline state is more efficiently packed than the liquid state), and thus reaching its thermodynamically preferred state. As the temperature is lowered the material, already crystalline, continues to decrease in volume due to thermal contraction.

In a high viscosity glass-forming melt, however, the temperature is lowered faster than the atoms can reform into the crystalline state. Instead, the melt increases in viscosity[15], and enters the super-cooled liquid state where there is short range, but no long range, order. The super-cooled liquid continues to undergo thermal contraction until its viscosity is so high that over the glass transition temperature range (or "glass transformation range") it becomes a 'glass' solid with no tendency for flow behaviour.

Glass is thus characterised by a lack of long range order. This means that glass is not a chemically definable material[16], but a state of matter as illustrated in Figure 3.2. All

[15] Viscosity is a measure of the material's resistance to flow; a manifestation of the difficulty of diffusion on an atomic scale.
[16] Theoretically speaking, any material can form a glass assuming that the temperatures are reduced fast enough to prevent crystallisation. In practice, however, most glasses are formed from materials with a high enough viscosity to prevent the formation of a

archaeological examples of glass (including obsidian)[17], however, are silicates, and the man-made examples are typically obtained from sand, flint or quartz pebbles combined with other ingredients in order to lower melting temperature and increase stability.

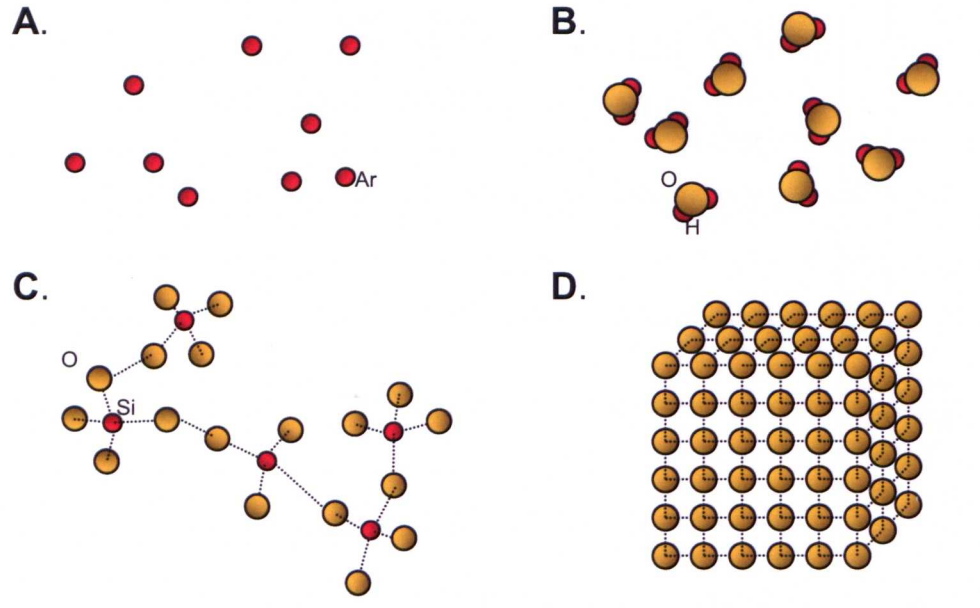

Figure 3.2 Levels of Atomic Arrangement in Gases, Liquids, Glasses and Crystals:
(a) Inert gases (e.g. Ar) have no regular ordering of atoms.
(b,c) Some materials including steam (b) and silicate glasses (c) have ordering only over a short distance.
(d) Metals and many other solids have a regular ordering of atoms that extends throughout the material.
After Askeland 1998, 39.

The silicate tetrahedron, shown in Figure 3.3, is the basis for all silicate glasses and the manifestation of short-range order. Bonds within a tetrahedron have identical bond angle and length, but the tetrahedra are joined to one another via oxygen 'bridges' of varying bond angle and bond length which is why the structure has no long term periodicity (Askeland 1998, 38 – 39).

In order to lower the melting temperature of a silicate-based glass, a flux (predominantly alkali, such as soda, Na_2O), or 'network modifier', is added to the glass melt. Alkali fluxes can be added in the form of plant ash, tree ash or mineral matter such as natron. The flux allows some of the SiO_4 tetrahedra to form non-bridging bonds (i.e. not bonded to other silicate tetrahedra), 'opening' up the network and thus lowering the melting temperature. The bonding between silicate tetrahedra and other ions is illustrated in Figure 3.4.

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crystalline structure under cooling conditions which are slow enough to prevent high stress to the cooled material. Even with their high viscosity, most glasses require the secondary period of slower cooling – annealing – at temperatures below the limit of the glass transition range. It is possible to produce metallic glasses; but these can only currently be formed into very thin ribbons due to the necessity of throwing the molten metal over a cooled copper wheel in order to achieve the glassy state.

[17] Obsidian is a naturally-formed glass.

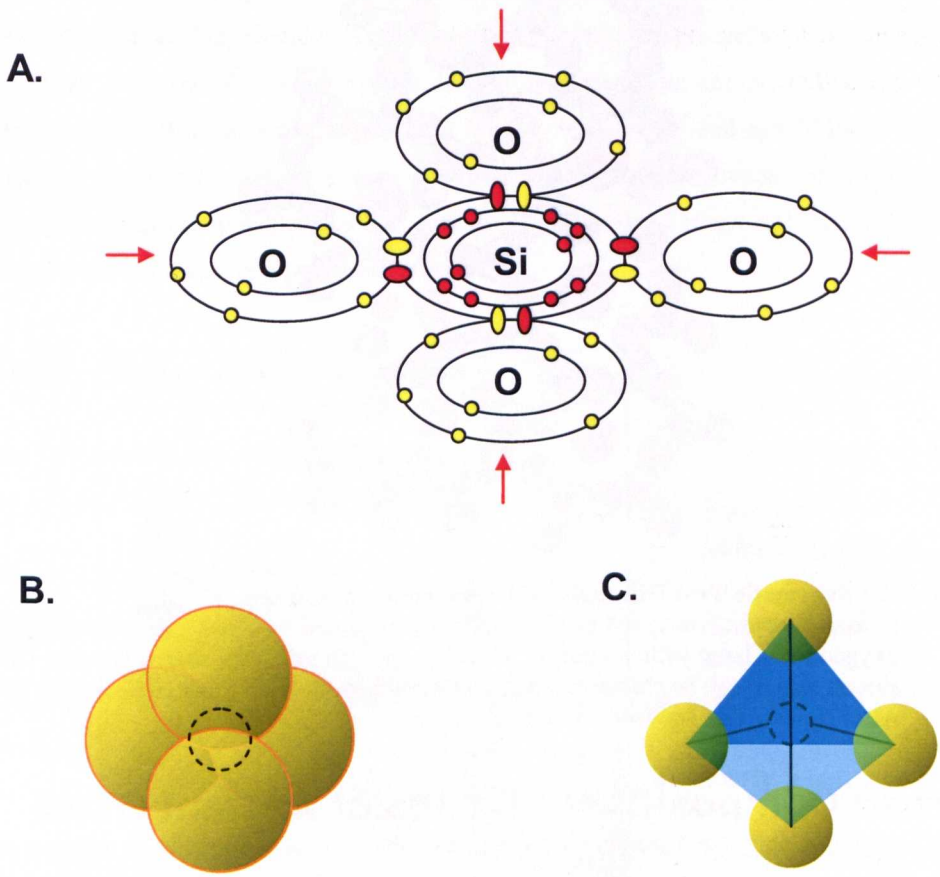


Figure 3.3 Stylised Representation of a Silicate Tetrahedron.

A. To attain a stable outer shell of eight electrons each Si atom (here coloured red) shares its outer electrons with four O atoms (here coloured yellow), becoming an ion, Si^{4+}. To fill their own outer shells O atoms can bond with two silicon atoms becoming ions O^{2-}.

B. Covalent bonding as described in 'A' is directional, so that any five ions linked in this way form a regular tetrahedron. The dashed circle represents the location of the smaller Si ion, at the centre of the four O ions.

C. Expanded view of 'B' showing the O ions located at four corner positions, equidistant from the Si ion.

After Skinner et al. 2004, 85.

Because alkali ions, in particular Na, are highly soluble in water, less soluble ions such as calcium (available as lime, CaO) are required to act as 'network stabilisers', holding the network together and preventing weathering (corrosion) through dissolution in water (Henderson 2000, 29). Thus most surviving examples of ancient glass exhibit a basic soda-lime-silica composition. It is likely that many glass making recipes required only two main raw materials, however: where used sand is often calcium-rich owing to the presence of shell fragments, and sources of soda such as plant ash could also contain calcium salts (Lambert 1997, 105).

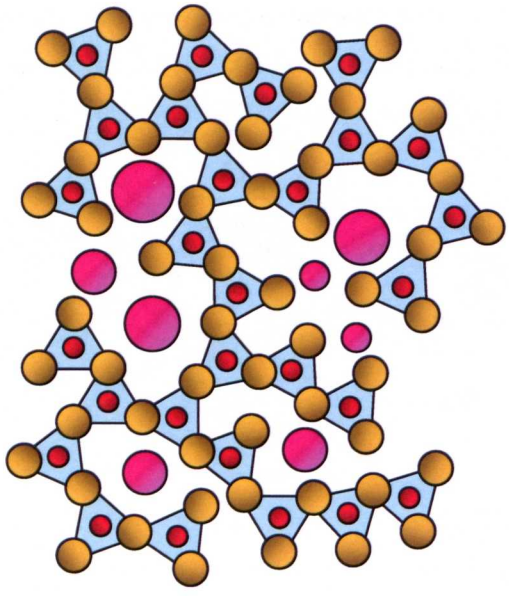


Figure 3.4 Schematic Two-Dimensional Representation of Glass.
Silicon ions are (small red circles), each accompanied by three – in reality four – oxygen ions (large yellow circles). Where an oxygen ion is not shared between two silicon ions, it can be chemically associated with another ion (pink circles).
After Newton and Davison 1996, 6.

Broad Compositional Trends of Ancient Glass

Within any time period and area involved in glass making there is bound to be a degree of variation with regard to the minor compositional characteristics of the glass produced. With this in mind, however, there are some very broad compositional characteristics of glass which relate to the dominant recipes used in their manufacture, as shown in Table 3.1.

	Egyptian 15th century BC	Roman 1st century AD	European 13th century AD	Syrian 14th century AD	Modern
Silica, SiO_2 (wt.%)	65	68	53	70	73
Soda, Na_2O (wt.%)	20	16	3	12	16
Potash, K_2O (wt.%)	2	0.5	17	2	0.5
Lime, CaO (wt.%)	4	8	12	10	5
Magnesia, MgO (wt.%)	4	0.5	7	3	3
Batch Materials	plant ash quartz	natron sand	wood ash sand/quartz	plant ash sand/quartz	synthetic compounds
Glass Category	high magnesia	low magnesia	forest glass	high magnesia	

Table 3.1 Broad Compositional Characteristics of Selected Categories of Ancient Glass.
The components are given in weight percent.
After Freestone 1991, 40.

Sayre and Smith (1961) were among the first to outline this variation and suggest that certain key oxides[18] are useful for differentiation between glass groups, as shown in Figure 3.5. They suggested five categories of ancient Western glass: second millennium BC, antimony rich, Roman, Early Islamic and Islamic lead (Sayre and Smith 1961, 1825). Although these have inevitably been modified since, the major trends noticed are still relevant to research conducted today, and provide a useful background from which to examine more specific compositional features[19].

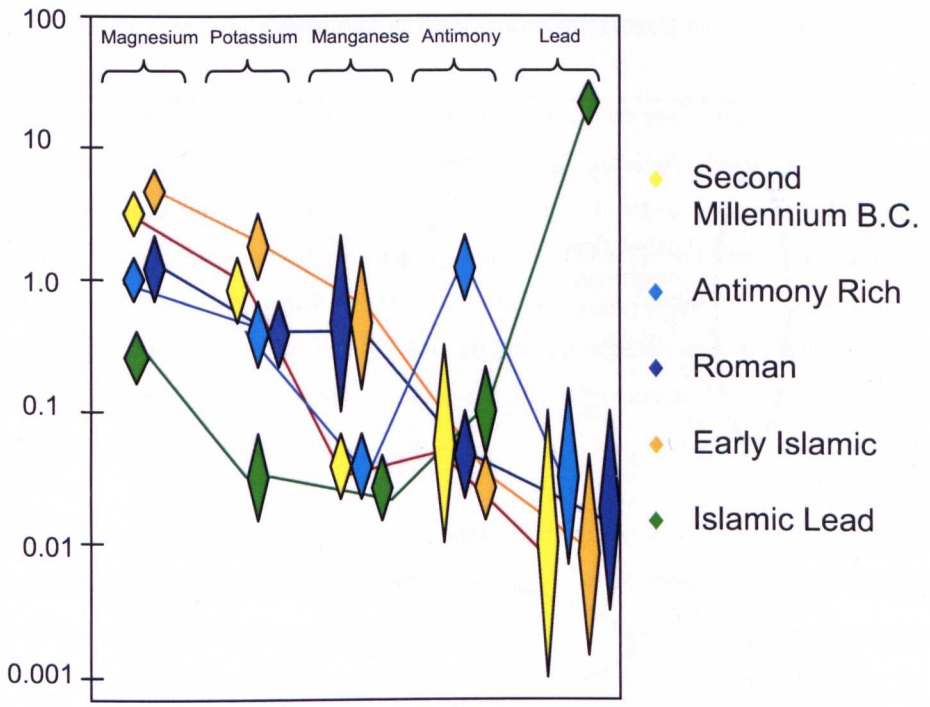


Figure 3.5 Standard Deviation Ranges for Concentrations of Selected Metal Oxides in Five Categories of Western Glass.
After Sayre and Smith 1961, 1825.

As noted by Sayre and Smith, most glass of the Late Bronze Age is characterised by its high magnesia content (HMG), corresponding with elevated potash. The other group of glass to emerge during the second millennium is characterised by low magnesia (LMG), including some Mycenaean examples, some cobalt blue glass found in Egypt and glass from Pella, Jordan (Henderson 2000, 57 – 58). A third group, characterised by low magnesia (<2%) and high potash (7 – 13%) and thus known as LMHK was identified by Henderson (1988a).

[18] Although references to 'iron' and 'manganese', etc., are made in the text, it should be noted that it these are almost exclusively present in glass the form of oxides, due to the chemical structure of glass outlined above.
[19] Table 3.1 and Figure 3.5 also draw our attention to the fact that not all archaeological examples of glass are soda-lime-silica based: the most notable examples are high-potassium European Medieval glass (see Table 3.1), and the high-lead Islamic composition (see Figure 3.5).

The relative levels of magnesia and potash for these categories of glass are illustrated in Figure 3.6. It is thought that in general LMG glass can be related to the use of a mineral alkali such as natron, the main period of use of which was from the 8th century B.C. to the mid 1st millennium A.D. in Western Asia and the Mediterranean in particular. HMG glass, on the other hand, was made with plant ash as a flux, and is found in a number of regions and time periods (Henderson 2000, 58). The LMHK composition is thought to be consistent with the use of a mixed alkali source, or possibly ashed vegetal matter from as yet unidentified plants (Henderson 1988a; Henderson 1988b) and is particularly characteristic of European glass from the 11th to 7th centuries BC.

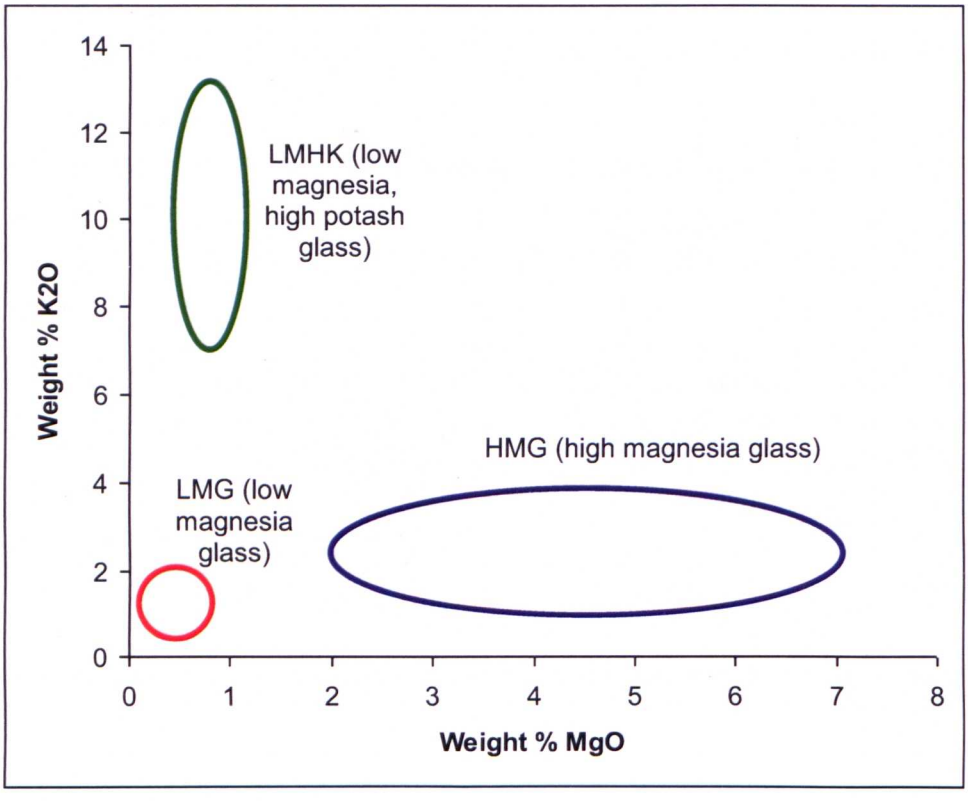


Figure 3.6 Compositional Variation in Magnesia and Potash.
Chart plotting magnesia (MgO) versus potash (K_2O) by weight percentage, showing the fields in which glass made with natron, plant ash or a mixed alkali source are thought to plot.
After Henderson (1988a).

Sayre and Smith (1967, 281 - 293) further characterise second millennium B.C. glass as belonging to a group with relatively high levels of magnesia (ave. 3.6%) and potash (ave. 1.1%) and low levels of decolourants such as antimony (with the obvious exception of antimony-opacified glass: see below). This is characteristic of the earliest glass up to about the 8th century BC, when antimony comes into common use as a decolourant and the levels of magnesia and potash decline as natron begins to replace plant ash as the preferred alkali source.

Owing to several factors, including the impurity of raw materials used, possible leaching of elements from crucibles and associated equipment, and the ritual activity and degree of conservatism which is thought to have prevailed in most periods in the complex process of glass production (Newton 1978, 175) numerous chemically unnecessary components may have frequently been included in early glass recipes (Shortland 2000c, 43 – 44). The possibility that chemically unnecessary ingredients may have been added to glass melts should thus be borne in mind when drawing conclusions about the composition of ancient glass, although it is equally true additional organic species would have been burnt off under the high temperature atmosphere required to form glass.

Colouring agents may have been added after the reduced frit[20] was cooled and finely ground (Newton 1978, 175). Early awareness of the different effects of oxidising and reducing atmospheres is made evident in the Mesopotamian recipes (which, as noted in Chapter 2, may or may not refer to glass): to manufacture the red material described it is specified that the batch, which contains copper, must be heated in a smoky (i.e. non-oxidising / reducing) fire and the finished product allowed to cool inside a closed oven whereas the blue material required a smokeless fire (Oppenheim 1970), thus keeping the copper in its blue oxidised state.

Recent trace element analyses of 54 samples of Egyptian and Mesopotamian glass by Shortland et al (2007) provide some evidence in favour of the manufacture of coloured glass through the addition of specific colouring / opacifying ingredients to a pre-formed colourless or faintly coloured glass (henceforth referred to as the 'two-stage' model of glass production). The presence of a number of trace elements at similar levels in both coloured and colourless glass (but different for Egypt and Mesopotamia) suggests that Egypt and Mesopotamia each made colourless glass to which colorants, with their attendant trace element signatures, were added in a separate stage (see Shortland et al 2007, 786 – 787). It should be noted that colourless glass in this sense refers to *uncoloured* glass which does not contain deliberately added colorants or opacifiers: this is referred to as 'naturally' coloured glass when encountered in later periods (see below).

Scientific Background to Coloration

The means by which various elements within a glass batch affect its colour are varied and complex: among the processes that affect glass coloration are the absorption bands of the elements within the glass, the redox conditions in the glass furnace, and the chemical environment and valence states of the elements within the glass itself. For example, if the same amount of potassium oxide was used in the place of sodium oxide in a glass which otherwise had an identical chemical composition, a deeper / darker colour would be imparted, as greater light absorption occurs in the presence of a heavier alkali (Henderson

[20] Assuming the fritting process was undertaken (see Chapter 2).

2000, 30). Likewise, several elements can impart different colours to the glass depending upon whether they are present in their oxidised or reduced form (Green and Hart 1987, 271 – 272), something affected not only by redox conditions in the furnace but also by the presence of other elements within the glass which act as reducing or oxidising agents.

The colour observed in a glass is a consequence of the absorption and emission of the electron clouds of its constituent ions (Vogel 1994, 223). White light is made up of a range of wavelengths and from *circa* 400 to 800nm this range falls within this visible spectrum. If one or more of the wavelengths corresponding to a particular region of the visible spectrum is lacking, a colour is perceived. The overall transmission and reflection properties of a glass result from a combination of the effect of reflection at the glass surface interfacing with the surrounding medium, and the effect of optical absorption in the body of the glass itself (Bamford 1982, 1). In a glass irradiated by white light, mobile electrons of the outer electron shells of certain ions accept energy of a particular wavelength leaving the remaining light without energy of that wavelength (Vogel 1994, 223).

In transition metals one of the energy shells, the 3d sub-shell, is only partially filled with electrons, causing resonance absorption in their electron clouds under white-light irradiation and producing colouring characteristics (Vogel 1994, 226). The simplest method of producing coloured glass is thus the introduction of '3d' elements such as iron, manganese, nickel, copper and cobalt into a base (colourless or nearly colourless) glass: when coordinated with other ions, such as Si^{4+}, the energy levels of the d electrons in transition metals are split (distorted) by the electric field produced by the coordinating ions. This splitting is sensitive to the chemical environment (the arrangement of surrounding ions) and the result determines the glass colour (Weyl 1976, 3 – 16, 70 - 71). The theory governing these effects is known as 'ligand field theory', the ligands being the outer atoms or molecules which form the coordination complex or compound. Even a small alteration in the ligand field may cause enormous changes in absorption behaviour and thus in coloration (Vogel 1994, 227), and this is responsible for the difference in colouring effects transition metal ions impart when their chemical environment is changed (for example, from ore to glass).

Scientific Background to Opacification

Opacification is usually caused by crystal inclusions within a glass having a refractive index different from that of the matrix in which they are dispersed; this may occur through refraction, reflection, diffraction or opalescence (dichroism), with absorption (see above) also affecting the appearance of the glass (Vogel 1994, 263 – 264). Opacity can also result from the presence of trapped microscopic air bubbles within the glass – often a result of low melting temperatures – and this along with deepness of colour accounts for the

apparent opacity some of the earliest blue glass vessels and beads (Stern and Schlick-Nolte 1994, 20).

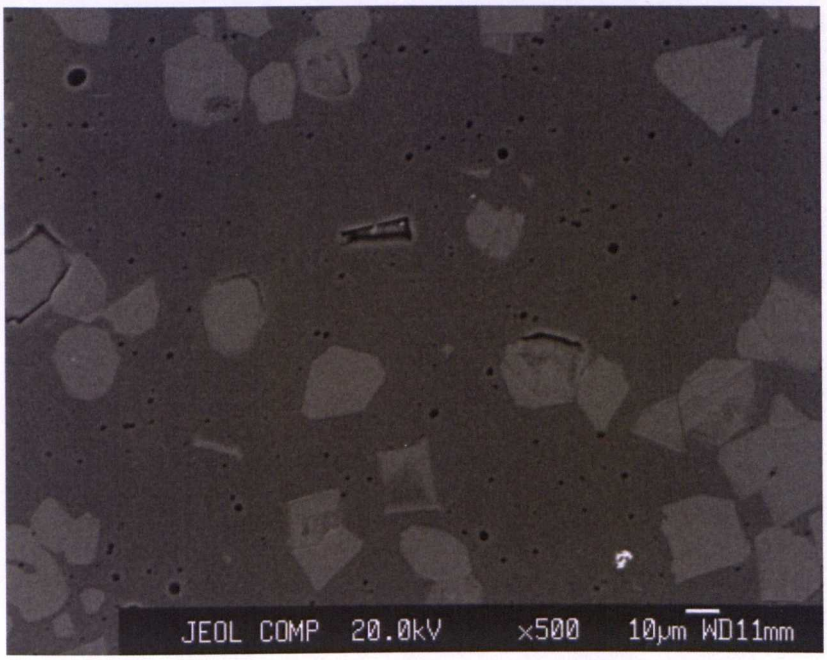


Figure 3.7 Silica Crystals within a Glassy Matrix.
Back-scattered electron image of MAA 1927.1478.

Crystalline opacifiers may be deliberately added to the glass or developed out of the glass by heat-treatment ('striking'). Any impurities present, such as relict silica crystals which have not completely dissolved in the glass melt or which have formed through a process of devitrification, as shown in Figure 3.7, will have a different refractive index from the bulk glass and can therefore also cause opacity.

Microscopic examination of the properties of the crystals that are present in archaeological samples of opaque glass can reveal details about possible modes of production. Three commonly encountered inclusion forms, imaged using EPMA (BSE), are illustrated in Figure 3.8. The delicate, fine morphology of the image in the top left suggests *in situ* precipitation from the melt since such a fine structure could not survive intact upon addition to a glass. Euhedral (evenly shaped) cubic crystal forms, such as those seen in the image on the top right, have also been suggested as evidence of precipitation from the glass melt (Mass et al. 1998, 121 - 133). It should be noted, however, that the more robust structure of the cubic crystals shown may help to limit their fragmentation or dissolution. The image in the bottom of Figure 3.8, by contrast, shows no remaining evidence of crystal faces. This may be the result of dissolution, or rapid crystal growth (by species within the glass melt which are preferentially precipitated and thus do not follow the glass cooling curve discussed above).

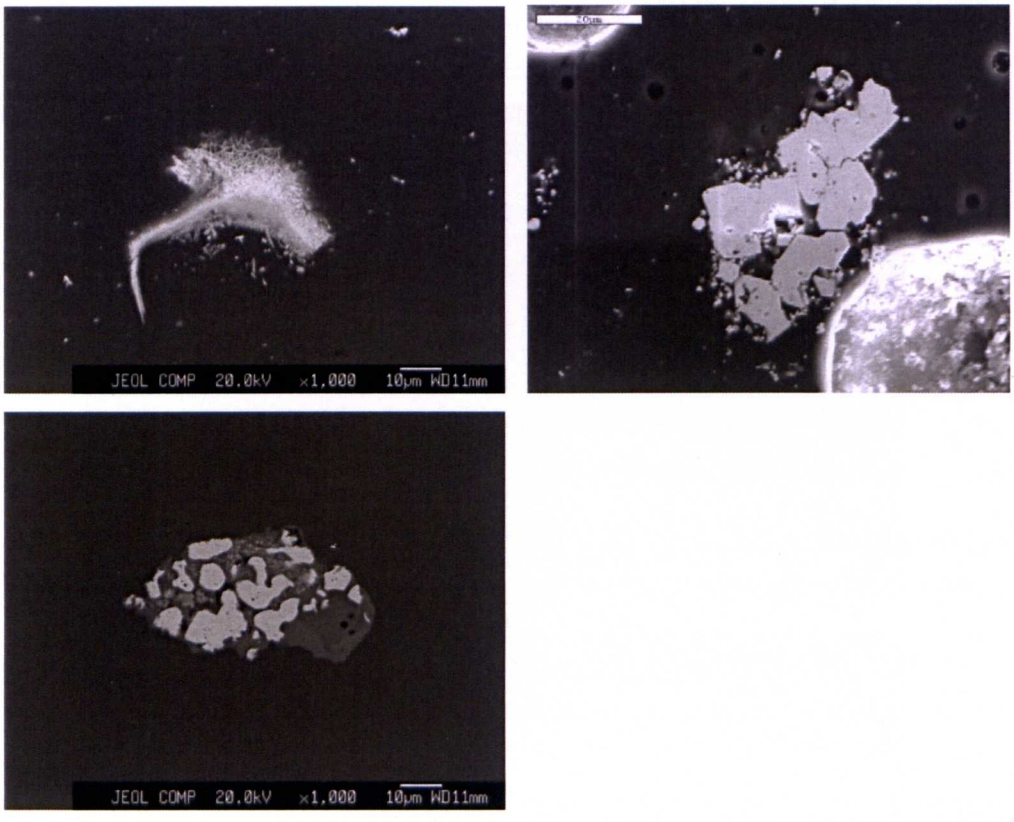


Figure 3.8 BSE Images Showing Examples of Crystal Morphology within Samples of Opaque Glass.

Top Left: acicular (needle-like) crystals (MAA 1947.1965).
Top Right: cubic crystals (MAA 1932.408I).
Bottom: inclusion with no clearly defined crystal faces (MAA 1947.1965JIII).
Images were taken during EPMA analysis in the present study.

Outward *in situ* growth may also be visible as compositional zoning within crystals (where the elements precipitate in sequence from least to most solvent in the glass melt), or in branching crystal forms. An example of branching, 'dendritic' growth patterns of copper in the formation of red opaque glass is shown in Figure 3.9. This delicate structure provides a clear example of formation by crystallisation from the glass itself as it was cooled, or alternatively during heat treatment ('striking').

Where particles are present as streaks throughout the glass as shown in Figure 3.10 (top), this is thought to indicate the late addition of components (mixing of different glasses, or the addition of raw ingredients or a sintered preparation); the glass has begun to solidify before completion of the mixing necessary to give a uniform distribution through the glass (see Shortland 2000c). On occasion, a small degree of mixing also occurs between the boundaries of two distinct colours of glass where these have been fused under heat treatment, as illustrated in Figure 3.10 (bottom).

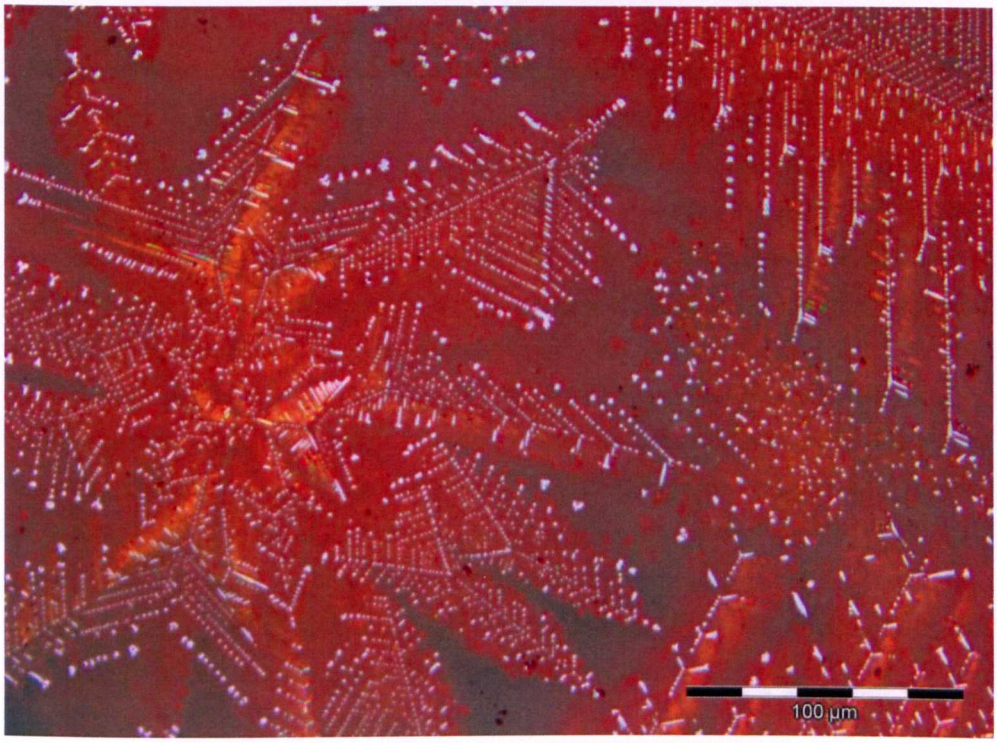


Figure 3.9 Dendritic Growth Pattern of Copper in a Sample of Red Opaque Glass.
The image was taken with an Olympus BX51 optical microscope. The image is of MAA 1947.2012 (not sampled in the present study).

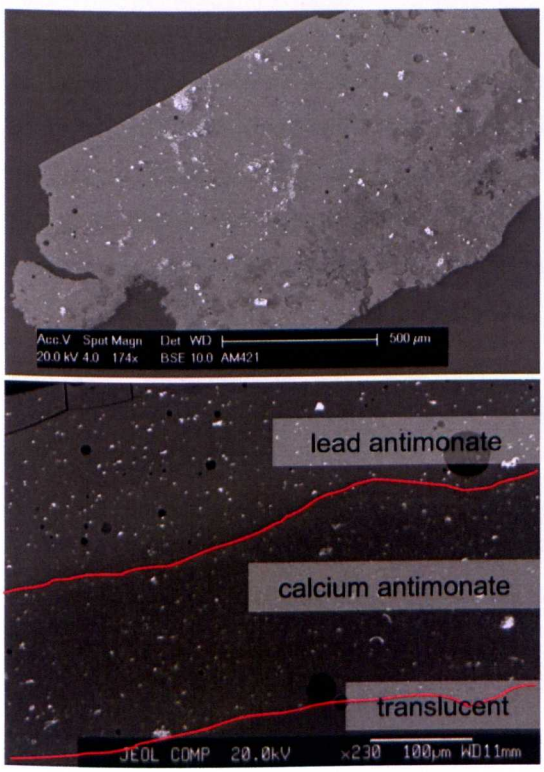


Figure 3.10 Heterogeneity between Opacified Regions of Glass.
Back-scattered electron images.
Top: Amarna 421, sample imaged courtesy of Julian Henderson.
Bottom: MAA 1932.4121.

'Natural' and Colourless Glass

Deliberate decolouration by the addition of other materials (decolourants) does not seem to have been practised in the earliest glassmaking. It may have begun as early the 8th century BC in Western Asia (Stern and Schilck-Nolte 1994, 21), however, and was certainly deliberately practised by the late 5th century BC as shown by examples from Olympia and Rhodes (Ignatiadou 2002, 11). 'Natural' glass refers to that which has a faint tinge of colour owing to (largely iron) impurities carried over from the raw materials used, and it is this which is thought to have produced the small quantity of colourless (uncoloured) glass known from the Late Bronze Age.

Iron and sulphur can be responsible for a range of so-called 'natural' colours in translucent glasses depending on the redox conditions the glass melt is exposed to, i.e. the atmosphere in the furnace. Iron is introduced into glass as an impurity in the silica source. It is thought that sulphur can be introduced by either plant ash or natron, or brought in with sand via crushed shells (see for example Schreurs and Brill 1984, 207). Almost all glass will have a hint of colour unless deliberately treated with decolourants, as even a small amount of iron can have a great effect on the colours produced (Weyl 1976, 97).

The relationship between atmosphere and iron-related coloration is shown in Figure 3.11. Under strongly reducing conditions the Fe^{2+} ion is present leading to a blue colour in the glass. Under strongly oxidising conditions the Fe^{3+} ion is created, imparting a brown or yellow colour to the glass. The two are otherwise present in roughly equal quantities, leading to various shades of green (Henderson 2000, 34). The presence of other ions can also affect coloration so that Fe^{3+} will tend to colourlessness in the presence of fluorides and phosphates (Shortland 2000c, 2). Sulphur, the effects of which are also illustrated in Figure 3.11, is responsible for producing a more orange / amber (rather than the yellow produced by iron alone) colour under oxidising conditions.

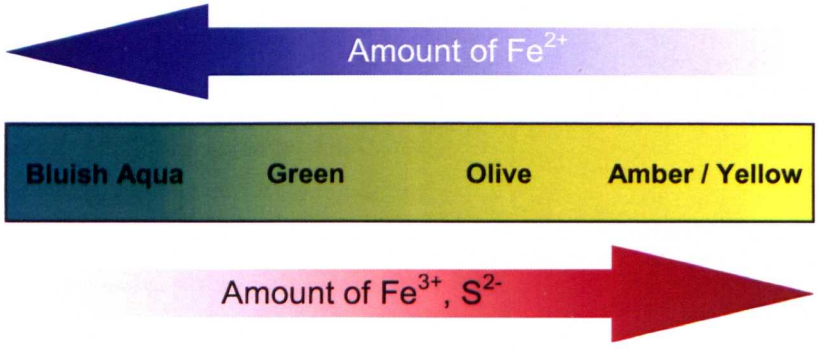


Figure 3.11 Effects of Ferric and Ferrous Species and Sulphur on Glass Coloration.

Likewise, manganese in the Mn^{3+} or Mn^{4+} states results in violet and pink colours respectively, but a much fainter (purple) colour in the Mn^{2+} state (Green and Hart 1987,

276; Lambert 1997, 113). Similarly, manganese can be reduced and iron oxidised in one reaction, the highly coloured forms of each being replaced by their less coloured forms:

$$Mn^{4+} + 2Fe^{2+} \rightarrow Mn^{2+} + 2Fe^{3+}$$

Anywhere from 0.1 – 1.6% MnO must be added to achieve this (as an unintentionally added impurity MnO is rarely present above c. 0.04%). The residual faint purple colour of the reduced manganese can also compensate for the yellow coloration of the Fe^{3+}, further increasing the effects of decolourisation (Weyl 1976, 121). Antimony is also a decolourant where it picks up negatively charged electrons from iron and is reduced to the less highly coloured +3 oxidation state (Lambert 1997, 111). The presence of other colouring ions, such as copper or cobalt, however, will largely eclipse the coloration effects of iron, sulphur and even manganese.

The rarity of LBA colourless glass has been noted elsewhere (see Riefstahl 1972, 11) but this does not necessarily preclude the possibility that glass was created in an initial stage (see above) and later coloured. The use of colourless or nearly colourless glass (as opposed to that with a stronger 'natural' tinge) does survive in some objects: it has generally been noted in unusual pieces such as a unique fish-shaped bottle in the Brooklyn Museum (316E, Abbott Collection) or the 'cover' for inlaid eyes from the throne of Tutankhamen (see Chapter 4). Colourless glasses from the XVIII Dynasty sites of Malkata and Amarna were recently subject to WDX (Shortland and Eremin 2006) and LA-ICP-MS (Shortland et al. 2007) analyses. They were found to contain an average of 0.4% FeO.

The chemistry and raw ingredients of the various colours of glass discussed in the following pages are summarised in Table 3.2.

White Opaque Glass

Opaque white glass of the Late Bronze Age was produced by the addition of antimony-rich minerals. Although tin dioxide (SnO_2) crystals can also act as an opacifier and colouring crystalline pigment in white opaque glass (Heck and Hoffmann 2000, 349) no tin-based opacifiers have been detected in ancient glasses until the second half of the 1st millennium B.C., and the earliest examples known are from Iron Age Europe (Henderson 2001, 477).

Calcium antimonate does not occur naturally as a mineral. As first noted by Turner and Rooksby (1959), however, when added to a soda-lime-silica glass melt antimony reacts with the calcium content already present as a stabiliser, and calcium antimonite ($Ca_2Sb_2O_7$ and $CaSb_2O_6$) is produced.

Glass Colour	Colouring / Opacifying Chemical Components	Suggested Raw Ingredients
White Opaque	Sb	Sb added in raw form and combines with Ca present in the glass to form calcium antimonate. Shortland (2002) suggests stibnite (Sb_2S_3), from Iran, Anatolia or the Caucasus as a source of Sb. Other sources include cervantite, Sb_2O_4, found in the Egyptian Eastern Desert, Turkey and Morocco.
Yellow Opaque	Sb, Pb	Pb and Sb added and form lead antimonate. Brill (1970) suggests lead antimonate may have been an article of trade. Natural occurrence together in the mineral bindheimite has also been noted. Pb and Sb could have been combined artificially to form a colorant. Zn also present in some: may suggest use of galena for Pb component.
Green Opaque	Sb, Pb, Cu	Can be made by mixing preformed blue and yellow opaque glasses; by mixing one preformed glass with one or more of the other colouring ingredients; or by adding all colouring ingredients in a raw or pre-prepared (e.g. sintered) state.
Light Blue	Cu / Fe	Cu causes light to medium blue colour under oxidising conditions. 0.5 – 3% Cu is common for LBA Egyptian material. Sn is sometimes associated with Cu suggesting the latter was added in the form of bronze. Iron can cause pale blue under strongly reducing conditions.
Turquoise or Blue Opaque	Sb, Cu	Can be made by mixing preformed blue and white glasses; by mixing one preformed glass with one or more of the other colouring ingredients; or by adding both colouring ingredients in a raw or pre-prepared (e.g. sintered) state.
Dark Blue	Co	Co present over 0.05% will affect colour of glass. Correlation with Mn, Zn, Ni, and Al in New Kingdom glasses points to use of cobalt-bearing alums from oases of Western Desert.
Purple	Mn	Compositional similarity to colourless glasses suggests a relatively pure Mn mineral source, such as pyrolucite, was added to a colourless glass.
Red Opaque	Cu	Cu causes opaque red under reducing conditions. Pb can aid formation of red when present over 1% but earliest examples of this are from the 6th century BC. Sn present in New Kingdom red glasses suggests use of bronze as a 'raw' ingredient.
Brown or Black	Cu / Co / Mn / Fe	Cu, when present in a glass with sufficient Fe, will cause a brown colour. Brown can also result from attempted production of red. Concentrated Co or Mn can result in a black appearance. High levels of reduced Fe can also result in dark brown – black.

Table 3.2 Glass Colorants and their Raw Ingredients
Summary table of previously published results and suggestions: drawn using the sources and arguments discussed in the text.

Shortland (2002, 522) has suggested that antimony was deliberately added to the glass melt in the form of a simple compound such as an oxide or a sulphide. Stibnite (Sb_2S_3) is such a compound, and was already used as a cosmetic in Egypt by the start of the XVIII Dynasty (Lambert 1997, 111). Stibnite is the primary antimony ore, occurring quite widely in sulphide deposits and is frequently associated with lead, silver and gold ores (Shortland 2000c, 50).

There are currently three possible known sources for stibnite in the Near East: Iran, Anatolia and the Caucasus, but of these the Caucasus is the only one showing direct

evidence of exploitation in antiquity. Mining here began in the 17th century BC but did not become large-scale until the Late Bronze Age, and more objects of antimony have been identified in the Caucasus than in the rest of the Near East combined (Shortland 2002, 526).

Stibnite is also often oxidised to yellow antimony oxides such as cervantite, Sb_2O_4. This could be found in a wider number of locations, including (potentially) the gold mines at Wadi Ballit in the Egyptian Eastern Desert and Fawakir, quartz veins at Gebel el Ineigi, East of Edfu and Turkey and Morocco, some of which are known to have been mined in antiquity (Shortland 2000c, 50). The use of stibnite in Egyptian kohls has also been speculated upon although this seems to make up only a fraction of the total kohl (Shortland 2000c, 50).

In a study of glass from Amarna, Shortland (2002, 519 – 522) removed the appropriate (stochiometric) ratio of calcium and antimony from bulk glass analysis and normalised the results. The outcome suggested that glass containing antimony possessed the same level of calcium as its calcium antimonate free counterparts. It was thus suggested to be unlikely that preformed calcium antimonate had been added as the opaque calcium glasses would be expected to feature raised levels of calcium.

Yellow Opaque Glass

From the second millennium to the second century BC opaque yellow glasses in Western Asia, the Mediterranean and Egypt were coloured and opacified by what are thought to be lead antimonate ($Pb_2Sb_2O_7$) crystals (Henderson 2001, 477; Brill et al. 1974). There is as yet no archaeological evidence for a possible production location of yellow glass during the Late Bronze Age. Although some lumps of yellow glass have been found off the coast of Israel no further context for them is known (Rehren 2000a, 21).

Brill (1970) suggests that lead antimonate may have been an article of trade for at least 15 centuries. Of 57 minerals known in the natural world that contain lead and antimony, however, only nine - most of these sulphides - do not contain significant amounts of either transition metals or arsenic and the majority of these are very rare with none known to exist in Egypt or Western Asia (Shortland 2000c, 50). It has been noted, however, that lead antimonate occurs naturally as bindheimite, $Pb_2(Sb,Bi)_2O_6(O,OH)$, so an impurity of bismuth in ancient lead antimonate opacified glasses might indicate that bindheimite had been used as an opacifier (Henderson 2001, 477).

Other suggested sources of lead include antimonial litharge[21], derived from the cupellation of silver[22]. Mass et al. (2002, 69) have argued that this was the source of the lead antimonate in Bronze Age and Roman glass. The cupellation of antimonial silver ores mined by the Romans resulted in the production of large quantities of litharge contaminated with antimony, which may have served as a source of both lead and antimony for Roman glassmakers in the production of yellow and green opaque glass (Mass et al. 1998, 121 - 124). It has been suggested that LBA glassmakers used the same sources of opacifiers as the Romans (Mass et al. 2002, 70, 78 – 79) but the view has received strong criticism (see Rehren 2003) and another possibility is that lead was derived from an artificial, pre-formed combination of lead and antimony ore minerals (Shortland 2002, 52)[23].

The presence of zinc in yellow glasses has been suggested to indicate that the source of the lead for these was a lead ore deposit such as galena (PbS), presumably with significant amounts of sphalerite (ZnS) to account for the zinc (Shortland 2002, 524; Shortland 2003, 191). It has been argued on the basis of lead isotope analysis that most of the lead in Egyptian lead antimonate glasses originated from Gebel Zeit on the Red Sea coast (Shortland 2002, 523), though data for all lead ores in Egypt and Mesopotamia remain incomplete, and the glasses were not entirely consistent with the known fields for the ore sources.

Lead antimonate yellow glasses from Amarna analysed by Shortland (2002, 525) have been found to possess an arsenic to antimony ratio of about 0.006:1, slightly lower than that for white opaque glasses analysed in the same study, so that it has been suggested that the same source of antimony was used in the production of both white and yellow opaque glasses.

Green, Blue and Turquoise Glass

It is well established that a bright / light blue colour in glass was generally achieved using copper, whereas a darker blue is more often the result of the addition of cobalt (Brill 1992, 12), though the two also occur in combination and cobalt is rarely found in glass without

[21] Litharge (PbO) is the yellow polymorph of lead oxide that was produced in antiquity as a by-product of cupellation. During this process silver or gold-containing lead is heated under a flow of air and the lead metal is oxidised, forming the litharge.

[22] Where silver is extracted by heating its ores in contact with lead compounds.

[23] Rehren (2003, 188) notes that analyses demonstrate that litharge and cupellation hearth material are rarely if ever as rich in antimony as suggested, certainly not to the extent necessary to produce lead antimonate yellow. Further evidence against the theory that litharge was used is the absence of arsenic in anything more than trace levels in the yellow glasses: the vast majority of unrefined lead, litharge and cupellation hearth material indicate the presence of arsenic and antimony in about equal quantities, which should result in significant arsenic concentrations in the glass (Rehren 2003, 188).

the presence of some copper (Bamford 1982, 19). Iron can also produce a pale blue colour under strongly reducing conditions as a result of the simultaneous presence of ferrous and ferric ions (Weyl 1976, 95 – 96, 108) but this was not the cause of the blue colour in most ancient glasses.

The two ionic states of copper produce two correspondingly different colours in ancient glasses: a bright blue or turquoise when the cupric (Cu^{2+}) ion is present and a bright sealing wax red or a dull brown colour when the cuprous (Cu^{+}) ion is present. Under oxidising conditions the copper within a silicate melt forms the Cu^{2+} ion. Divalent copper Cu^{2+} can form colouring centres of differing co-ordination producing deep blue, light blue, green and even brown glass (Weyl 1976, 155).

Kaczmarczyk and Hedges (1983, 60) suggest that the relative abundance of copper in the Near East may be one reason for its common use as a glass colorant. Copper was used in Egypt from at least the Nagada I period (c. 4000 BC) in faience glazes, and is the most common form of colorant in early Egyptian glasses (Rehren 2000a, 21). Sayre and Smith (1974) note that Egyptian glasses deliberately coloured by copper contained CuO in the range of 0.59 – 1.45%, with an average of 0.93%; Shortland (2000c, 46) offers slightly higher copper contents for the glasses from Amarna, varying widely between 0.85% and 3.12% with an average of 1.45% CuO. It is likely that copper contents below 0.1% CuO are the result of accidental contamination from bronze or copper vessels and tools, owing to the high mobility of copper within a silicate matrix (Kaczmarczyk and Hedges 1983, 56 - 63).

Sayre and Smith (1974) suggested that the ratio of copper to tin in some contemporary glasses was compatible with the composition of New Kingdom bronze. In a study of glass from Malkata and Lisht, it was found that SnO_2 was present only in the light blue opaque (turquoise) Malkata glasses (Mass et al. 2002, 75). Significant levels of tin were also found in some copper blue samples from Amarna, suggesting that bronze may have been used to colour these too (Shortland and Tite 2000, 143). The lack of tin in glass *without* associated copper suggests that pure tin metal was not added to glass as a separate ingredient.

Opaque green glass can theoretically be made by mixing opaque yellow and translucent blue glasses, by adding lead antimonate to preformed blue glass or even by adding copper to preformed yellow glass. Similarly, blue glass could be rendered opaque by the presence of calcium antimonate crystals (see Mass et al. 2002, 76), either by mixing preformed white and blue glass, or by adding antimony and copper (or a sintered preparation of the two) to the glass melt.

Cobalt Blue Glass

The divalent cobalt ion Co^{2+} is responsible for the characteristic deep blue in early glass, although under the right conditions cobalt can produce colours ranging from pink and purple to green (Weyl 1976, 170) and can also be responsible for a slightly brighter ('indigo') blue and a violet colour (Shortland and Tite 2000, 143). Cobalt is the most powerful transition metal colorant: at its maximum the linear absorption coefficient of cobalt in glass is at least a factor of five greater than the other transition metal ions, so that less cobalt is needed in order to produce a given colour intensity than any of the other transition metal ions. As little as 0.05% CoO is enough to produce a deep blue colour in glass (see Henderson 2000, 29). In contrast to this, 0.5-1% FeO or 1-2% CuO are required to produce a reasonably strong blue.

Cobalt has been found in association with manganese, zinc, nickel and alumina in New Kingdom cobalt-coloured material (Kaczmarczyk and Hedges 1983, 46), and elevated amounts of these elements are also present in cobalt coloured glass of the same period. Based on this compositional evidence, cobalt-bearing alums found in the oases of the Western Desert of Egypt (in particular the Kharga and Dakhla Oases) are thought the most likely source of the cobalt used to colour LBA Egyptian glass (Shortland 2000c, 49). Although there is no modern economically viable source of cobalt in these Oases, there is abundant evidence that they were worked in antiquity for their deposits of alum.

Despite opposing claims that the analytical evidence suggests one or other of the oases as the particular source of cobalt in New Kingdom Egypt (see Kaczmarczyk 1987, 369; Shortland 2000c, 49), relative levels of the noted impurities in the final glasses are not *entirely* consistent with either the Kharga or Dakhla Oasis, so it has been suggested that the cobalt-bearing alum was modified in some way before use (Henderson 2000, 31). Cobalt can be precipitated as a hydroxide from an aqueous solution of the cobalt alum, using highly alkaline ammonia and heating the resulting gel to 800 - 1000°C to form the cobalt aluminate spinel (Tite and Shortland 2003, 294; Shortland 2000c, 49). Alternately, the alum could simply have been roasted in order to drive off the sulphur: in medieval Europe, it is known that a cobalt-bearing mineral (zaffre, or 'Damascus pigment') was roasted to remove any sulphur and arsenic before use (Rehren 2001, 484 – 488).

Aside from the presence of elements thought to be associated with the cobalt colorant, some glasses coloured by cobalt provide an exception to the general homogeneity of glass compositions at this time, in particular owing to their lower potassium content (Lilyquist and Brill 1993, 41). They do not fit satisfactorily into either the HMG nor LMG groups discussed above. Tite and Shortland (2003, 305 - 306) suggested that four different plant ash glasses, each with a distinctive composition, were used in the production of cobalt and copper blue glass and frits found at Amarna, and that it is possible only the cobalt blue

material was actually manufactured at Amarna itself. They also note the possibility that natron from Wadi Natrun was used as the alkali source for cobalt blue frits (Tite and Shortland 2003, 307), having rejected their earlier hypothesis that natron was used in the production of all cobalt blue vitreous materials at Amarna (see Shortland and Tite 2000). The major drawback to the suggestion that different plant ashes were used is the lack of detailed knowledge of plant ash compositions. More recent work by Barkoudah and Henderson (2006), however, has illustrated that compositional variability may be as much a result of the underlying geochemistry of the soil than species differentiation. Furthermore, Jackson and Nicholson (2007, 104), have pointed to the difficulties of relating the composition of cobalt coloured glasses to that of the alums, due to the heterogeneous nature of the latter and the unpredictability of element partition during processing of the alum.

LBA glass from the Baq'ah Valley, Jordan (see above), was found to contain cobalt along with the same trace elements as it is associated with in Amarna glasses, suggesting that this was acquired as a result of trade with Egypt, though it is not clear whether the cobalt was traded raw (possibly after some treatment was performed) or as part of preformed glass ingots manufactured at Amarna or other sites (McGovern 1992, 103). However, the 175 glass ingots found on the Ulu Burun wreck (see Chapter 2) demonstrate that 'raw' cobalt-blue glass was being traded in some volume.

Purple Glass

Although not as common as the other colours discussed here, there are examples of purple glass dating to the Late Bronze Age. Manganese, also used as a decolourant in glass, can impart a purple colour under the right conditions (see Weyl 1976, 121 – 127). Shortland and Eremin (2006) analysed nine samples of purple glass from Malkata and Amarna. All were found to be coloured by Mn at an average level of 0.89% MnO. Other than this they were found to be identical in composition to the colourless glasses analysed in the same study. It is thus likely that a relatively pure manganese mineral source such as pyrolucite (MnO_2) was used for the production of purple glass (see Henderson 2000, 34).

Red Opaque Glass

Red glass can be produced and opacified using metallic copper particles or cuprite, Cu_2O, and is the result of the strict maintenance of a reducing atmosphere during production (Brill 1992, 14; Mass et al. 2002, 69).

In copper-blue glass, the ions are dispersed individually throughout the glass and behave in the same way as does a dye (or copper sulphate) dissolved in water (Brill and Cahill 1988, 17). However, when a copper-containing glass is strongly reduced the copper is reduced to the cuprous (Cu) ion and particles of cuprous oxide (Cu_2O or cuprite) and / or

copper itself can be precipitated in suspension throughout the glass (Brill 1963, 126). This is achieved by 'striking'; reheating the batch at temperatures of 500 - 800°C (Welham et al. 2003, 14).

Red glass from Qantir, for example, has been shown to have been coloured by the distribution of cuprite as a phase with fine morphology, suggesting it was grown from an initially homogeneous melt (Freestone 1992, 180). This could have occurred as the glass was slowly cooled, or the glass could have been held within the temperature range mentioned above to encourage cuprite nucleation and growth (Freestone 1992, 180).

The presence of lead from about 1% and over increases the solubility of copper at high temperatures and causes this solubility to decrease rapidly as the temperature is lowered, thereby enabling more cuprous oxide to be precipitated and decreasing the threat of devitrification during the crystal formation necessary for its production (Brill 1963, 126). Lead also results in an increase in refractive index and optical dispersion, improving the clarity and colour of the glass (Freestone et al. 2003b, 145). Despite the early use of lead in the production of opaque yellow and green glass, however, the earliest evidence of its beneficial use in red opaque glass known to date is from the 6th century B.C. at Nimrud (see Cable and Smedley 1987).

Tin is also thought to be an aid to the formation of the red colorant (Brill and Cahill 1988, 19) although it does not help to produce a brighter red. A wide range of ancient glasses analysed by several different researchers (Geilmann 1955; Sayre and Smith 1974; Kaczmarczyk and Hedges 1983) were found to contain copper, tin and lead in proportions similar to those found in bronze of the same period (see Sayre and Smith 1967, 308). Adding copper to glass in the form of bronze scale from metallurgical workshops such as that at Qantir may have been easier than adding metallic copper, as bronze scale can be crushed and then dissolved quite readily in a glass melt (Brill and Cahill 1988, 22).

If the cuprite crystallites are suspended in a colourless glass matrix, the glass itself will take on the same bright red colour of the crystals, but if the matrix glass contains other colorants and has, for example, the aqua or greenish colour due to iron impurities, then the bright red colour of the crystals is modified to the brick red or muddy brownish colour typical of LBA red glasses (Brill and Cahill 1988, 18). This same colour is also produced if much dissolved copper, with its attendant blue or green transparent colour, remains unprecipitated in the matrix glass (Brill and Cahill 1988, 18). There is little evidence that the makers of the earliest red opaques (LBA Egyptian examples) had achieved the levels of decolourisation necessary to produce the brightest shades (see Brill and Cahill 1988, 18). This seems to contradict Shortland and Eremin's (2006) argument for a two-stage

model of glass production, but it should also be noted that even strong 'natural' colouring may have been enough to dull the red.

Red glass can also be produced by the addition of iron dispersed as spherical particles up to 2 microns in diameter (Henderson 2001, 476), and though iron colorants were rare in the glass analysed by McGovern (1992,100), two LBA – EIA (1550 – 1050 B.C.) samples from Beth Shan averaged 3.9% ferric oxide and a further LBA (1400 – 1200 B.C.) sample from the Baq'ah Valley contained 7.03%. No cupric red glass was found at either site (McGovern 1992, 100). Post 1200 B.C. 'glass' from both sites was found to contain exceptionally high levels of iron oxide (up to 47%), and McGovern (1992, 103) suggests it may have been reworked iron slag[24].

Segregation is known to occur when batch constituents which melt at relatively low temperatures form a fluid but very dense liquid which sinks to the bottom of the crucible (Welham et al. 2003, 12). Segregation in red glass may have been somewhat reduced by crushing the finished glass and remelting it (Welham et al. 2003, 13) or by using an initial partial melting stage followed by a full melt, i.e. fritting, some evidence for which has been found at Qantir (see Chapter 2).

Weyl (1976, 420) describes opaque red as the 'most difficult of all coloured glasses to produce'. Furthermore, the reducing atmosphere would have to be maintained while the glass was being worked (Brill and Cahill 1988, 18) to avoid the development of a surface layer of differently-coloured (oxidised) glass on the finished worked item: this limits the methods through which red glass could be formed into objects. Another possibility is that the red glass could be heated under a 'charcoal blanket' in order to maintain reducing conditions during the melting of the glass (Newton 1978, 175). In any case, the difficulties associated with the production of red glass have led to the suggestion that it may have required more specialised craftsmen and limited production locales (Shugar 2000, 375) than the production of, for example, copper-blue glass.

Brown and Black Glass

There are relatively few examples of brown glass from LBA sites in the East Mediterranean, Egypt or Western Asia. Brown beads from Merovingian (5^{th} – 7^{th} centuries AD) graves in France, Germany and the Netherlands were found in one study to have been mainly opacified and coloured by elemental copper with a grain size smaller than 1μm: the observed colour may have been influenced by the high concentrations of dissolved Fe and Pb present (Heck and Hoffman 2000, 349). CuO or Cu_2O would have been added and reduced to elemental copper in the glass melt, reducing conditions being caused by Fe^{2+},

[24] It is also possible, however, that analytical errors associated with the use of PIXE analysis were partially responsible for the exceptional results.

probably added in the form of magnetite (Fe_2O_3 FeO), acting as an internal reducing agent (Heck and Hoffmann 2000, 353). Opaque brown can thus be produced in a similar way and with similar ingredients to red, and since LBA red opaques are not of the bright, 'sealing wax' variety, but have been described as dull and 'liverish' in colour, it is possible to envisage a spectrum of opaque red glass for this period, with brown being an extreme form of the darker, duller reds of early glass production. Some colourless glass can also have a brownish tinge due to variation in the oxidation state of Fe in the furnace (see Shortland and Eremin 2006, 591).

Concentrated amounts of cobalt or manganese can produce very dark blue and violet respectively, causing glass coloured in this way to appear black. Some samples of second-millennium B.C. Mesopotamian glass were also found to be coloured with reduced iron (Stern and Schlick-Nolte 1994, 20) and it was found that manganese and copper were responsible for the colour of two black beads of glassy faience from Lisht (Lilyquist and Brill 1993, 22).

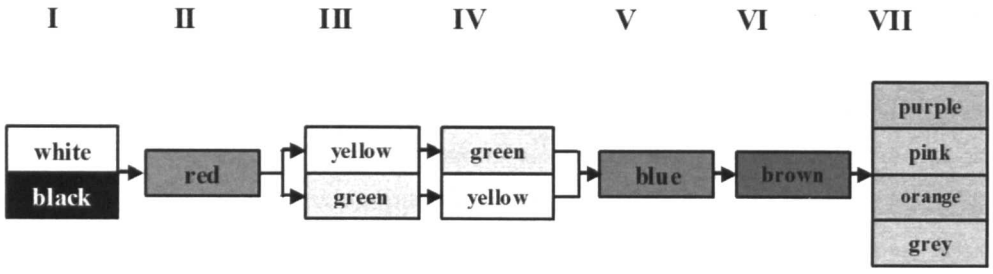
3.b. Archaeological, Linguistic and Historical Approaches to Colour

Jones (2004, 334) has pointed to colour as a key feature of materiality-based approaches. In particular, he notes the utility of archaeometric approaches revealing evidence about the selection of colour – relating colour to technological choice – when added to work on the symbolism and visual effects of colour which has, at least according to Jones, a longer history in archaeological thought[25]. The following themes and arguments are all of relevance to the treatment of LBA glass offered in the present work, and the ideas will be further developed in Chapter 4 which follows. Some of the themes developed here are well attested in the archaeological literature; for others, my own interpretations have been more strongly emphasised, albeit with reference to archaeological examples and previous studies.

Language and Colour: basic colour terms, universals and the Berlin and Kay paradigm

Systematic investigations into language and colour were initiated in response to the Whorf hypothesis which proposed a causative link between the linguistic naming of colour terms and the perception of colour. The seminal work published by Berlin and Kay (1969) challenged this by arguing that while the precise number of (linguistic) colour terms is seen to be culturally specific, the human perception of colour is universal. This was an important stage in the investigation of colour terms, and is based on evidence from cognitive psychology. They further suggested, however, that the order of use of various 'basic' colour terms builds up over time in the same pattern, regardless of the culture under examination. 'Basic' colour terms are defined by their generality and salience: they are general because their meaning is not subsumed by other terms and they apply to a diverse array of objects, whereas their saliency is defined by the frequency and consensus of usage within a given language (Jones and MacGregor 2002, 4). Thus, according to what has become known as the 'Berlin and Kay paradigm', some languages use just two basic colour terms while others use the maximum of eleven (above which 'secondary' colour terms, but no more basic ones, may be added), and the hues or domains of colour being described will follow a set path, as illustrated in Figure 3.12.

[25] It should be noted, however, that analyses of pigments in fact began as early as 1815 with the work of Humphry Davy in his *Some Experiments and Observations on the Colours used in Painting by the Ancients*, and glasses themselves were being fairly extensively chemically analysed and discussed during the early twentieth century.



3.12 Linguistic Evolution of Basic Colour Terms after Berlin and Kay (1969).

It should be noted that the categories shown here have subsequently received some modification, a summary of which is given in Baines (1985, 283). The key modifications involve the replacement of 'green' in Stages III and IV for 'grue' (a mixture between green and blue), with the subsequent distinction between green and blue arriving at Stage V.

More than Munsell: after Berlin and Kay

More recently, elements of the Berlin and Kay paradigm have been questioned[26]. As well as the directionality of the system (implying a unilinear 'advancement' through the colour terms), it has been noted that the definition is based on a single attribute of colour, i.e. hue, often measured by recourse to standardised colour charts such as the Munsell (Jones and MacGregor 2002, 5), though it should be noted that this system also incorporates *chroma* (roughly, saturation) and *value* (related to brightness). In any case, that all humans *physiologically* perceive the full colour spectrum[27] regardless of linguistic or cultural factors remains unquestioned, but the way in which colour information is subsequently processed is now accepted as being rather more cognitively complex. Over and above the physiological mechanisms which form the basis of visual perception, the processing of information also depends on learning, i.e. knowledge gained via experience.

As noted by Carole Gillis (2004, 56), divorcing colour (hue) from material may be a uniquely modern concept, and other phenomena are now thought to influence the perception, description and classification of colour. Texture (for example wetness and dryness, as first noted with reference to Hanunóo colour categories of the Philippines by Conklin 1952, 342); darkness and light (see Rosch 1972[28]); and brilliance or shine (see Jones and MacGregor 2002, 14) may all affect the classification of colour. The history of

[26] For a more detailed discussion and criticism of the Berlin and Kay paradigm, in particular the use of Western colour categories as universals, see Chapman (2002).

[27] In that, aside from those with a form of colour blindness, all humans perceive colour of wavelengths from circa 400 to 800nm, through reception of light by three types of cone cells with different spectral sensitivities.

[28] Rosch (1972) illustrates the cognitive structuring of colour categories around perceptually salient 'natural prototypes'. This amply illustrates the difficulties of assuming universal colour foci, as what is salient varies from society to society and environment to environment.

the colour purple illustrates this point. Roman accounts of purple stress lustre above hue while, in the Medieval period the term 'purple' came to designate a thick quality of silk cloth which might be almost any colour including white or green (Gage 1993, 27) though it was nonetheless understood primarily as a colour term. In a study by Ziderman (2004, 40) it was suggested that ancient colour designations for textiles may be regarded as having one or more of three meanings:

Aesthetic	an abstract term for colour sensation or hue
Chemical	name of dyestuff substance (or if the system were applied to glass; colorant)
Coloured Material	e.g. dyed textiles as commercial commodities (or for glass, as above, coloured ingots)

Thus the identification of colour may relate primarily to a particular material or product even if it is understood as deriving from a description of hue. In a more tangible – to use the appropriate metaphor – example, ethnographic studies of certain groups of Mexican potters found that they were unable to match clay colours with standard charts because the charts lacked the features of wetness, texture, and smell that they considered essential in judging colour (Kaplan 1985, 358).

It is difficult to overestimate the importance of light and brilliance in colour perception and categorisation, as illustrated by numerous examples in archaeology and anthropology. Gage (1993, 26) notes the importance of light in the Graeco-Roman classification of colours: light and life were cognate concepts, and as early as the Mycenaean period we have evidence for the understanding of light as a sign of the epiphany of the gods. Indeed, the tradition of Graeco-Roman colour descriptions that persisted into the medieval period emphasised the value of light and shade *over* that of hue (Gage 1993, 27). Saunders (2002; 1999) discusses the cross-cultural significance of the effect of brilliance during the contact period in Mesoamerica: metal, natural (i.e. pearls) and glass objects exchanged between indigenous and colonial regions were re-evaluated by the two different communities on the basis of existing cultural paradigms, but significantly the properties of brilliance and shininess were held to be important by both groups of exchange partners. Among Australian Aborigines, the colour, brightness and quality of different stones are intimately connected and these properties affect the manner in which rocks are categorised and the ways in which coloured materials within the landscape are perceived and used (Jones and Bradley 1999, 113).

The importance of brightness and brilliance in a Late Bronze Age, East Mediterranean context has recently been highlighted in a study of Minoan faience by Tite et al. (2009), where experimental reproduction coupled with chemical analysis revealed that weathering of surviving objects has obscured both the brilliance and range of colours originally produced in this material.

Referring back to linguistic classification, many colour terms are indeed attributive and include all the visual qualities (including surface textures and in particular shininess) of a referent except the form and the shape (Chapman 2002, 48). Of relevance to the present work, this is evident in both the Egyptian and Mesopotamian list of basic colour terms: to those discussed in more detail in Chapter 4 may be added a texture term (*s3b* in Egyptian; ugun in Sumerian; *burrumu* in Akkadian) meaning 'variegated' or 'multicoloured' and used almost exclusively for animal skins, birds' plumage and snake skins (Baines 1985, 283).

Contrast and Apotropaic Properties

Dark and light, or dull and bright colours are often juxtaposed or interwoven in the manufacture of material culture, increasing the effect of the brilliance of certain colours (Jones and MacGregor 2002, 15). Jones and Bradley (1999, 114), with reference to the use of colour in Irish passage tombs, argue that the way in which colours are perceived and understood suggests we think of them as a series of contrasts.

Gell (1998, 74 - 80) explores the psychological aspects of decorative art: the result of dynamic alterations of, for example, dark and light, is said to cause a 'pleasurable frustration' in the viewer. The earliest written Greek records of colour, in the poetry of Alcmaeon of Croton (early 5th century BC) dwell on the antithesis between black and white, or darkness and light; Empedocles linked colour with the harmony of the four elements; and Democritus also spoke of four 'simple' (*hapla*) colours: white, black, red and *chloron*[29] which is 'composed of both the solid and the void' (Gage 1993, 11 - 12).

As will be discussed in Chapter 4, prized stones of the LBA world within the Mesopotamian and Egyptian spheres of influence were often recognised on the basis of colour and – of equal importance – colour contrast. The veining or mottling present on a stone were key to its value. Thus certain varieties of lapis lazuli were prized above others and a wide range of descriptive terms were used to refer to the particular patterning or contrast present. Certain contrasts within turquoise, too, were prized above others. Of the more abundant stones selected for grinding into jars and other forms, it is apparent that contrasting colours – again in the form of mottling (for example in certain types of

[29] Although this colour set appears to reinforce the strict application of the Berlin and Kay paradigm (here at stage III) the term *chloron / chloros* (χλωρός) stands as an example of the way in which linguistic categories cannot be read at face value. While generally taken to refer blandly to 'green', symbolic associations with this colour or hue meant that χλωρός could also be applied by the poets to wine, blood and even human limbs. This particular 'greenness' was perhaps more linked with the properties of being fresh, fecund and vital than with the particular hue to which it is also linked. Similarly, the colour term *glaukos*, although to some extent associated with light blue, could be used to describe a huge range of things from olives to the moon, and referred more to a glittering property than a particular hue (Deacy and Villing 2004, 85). For a more detailed discussion of the semantics of the early Greek work hoard see Clarke (2004).

limestone, limestone breccia and serpentinite) or streaks / veining (for example black veined marble or recrystallised limestone, gypsum or alabaster) were sought after and highlighted in the grinding and polishing process.

It should also be noted at this point that complex decorative art is often worn on the body and may have an apotropaic purpose. Boriç (2000, 39), citing examples in dress, suggests that apotropaic issues are central to the use of colours[30], and are often inseparable from the significance that decorative art carries; while the meaning of colour may vary cross culturally, this practice appears to be universally human. The 'artistic' elements on glass vessels, beads and amulets of the Late Bronze Age are generally decorative as opposed to representational. This is not to say, however, that they do not possess function, and apotropaic properties are certainly a key factor in the production of amulets (and beads which may also possess amuletic function) in a number of materials, including glass. The polychrome nature of many glass beads and other small objects may indeed have been related to these issues.

Colour Choice, Rarity and the Exotic

The frequent association of black, white and red in the archaeological record, in particular in the evidence for the early exploitation of colour, may provide some evidence as to the motivations and perspectives behind human selection and manipulation of colour. It has been suggested that the prominence of these three colours can be explained as relating on a primary level to the human body, and a cross-cultural association of these colours with the human body has been proposed (see Turner 1967). Here, red (and particularly in prehistory, red ochre) is associated with blood, white with bones and semen, and black with faeces. Boriç (2002, 24), though warning against over-generalisation, accepts that some aspects of such an approach are valuable, especially the proposition that the human body acts - or can act - as the immediate source of metaphors relating to the world at large. The association of white, red and black with fire has also been noted. Furthermore, the prominence of these three colours is consistent with the linguistic categories suggested by Berlin and Kay (see above), whose stage I involves a distinction between black and white (or darkness and light) and stage II adds a basic colour term for 'red'.

These two initial stages are indeed the least disputed in the application of the Berlin and Kay paradigm to archaeology, and their frequent occurrence together in vastly different

[30] The almost ubiquitous 'evil eye' bead of long tradition in the eastern Mediterranean in particular, serves as an example of how colour and contrast can serve an amuletic, apotropaic function (see Sode 1995). That glass is eminently suited to this purpose may in part be explained by its strength of coloration, its durability, shine, and the possibility of forming a small multi-coloured object out of drawn glass.

archaeological contexts has lent support to appeals for accepting the concept of universalities. Wierzbicka (1990, 140) argues that basic colour concepts are anchored in certain 'universals of human experience', arrived at through a range of ethnographic and linguistic evidence. Her 'universals' are as follows: day (white); night (black); fire (red); the sun (yellow); vegetation (green); the sky (blue); the earth (brown). Exceptions to such 'universals' are inevitable and one could argue that, just as the application of the Berlin and Kay paradigm to colour in archaeology may begin to collapse after Stages I and II, so is the concept of universal colour references – beyond the very simplest of interpretations – too complicated and too subject to other influences (different cultural or natural environments, etc.) to be of use as a general reference. The frequent association between colours and various physical and symbolic references, however, demonstrates the strength of colour as a referent, the symbolic links it may engender between features of the natural and created environment, and its importance as a means of communicating these factors. This use of colour as a means of communication is central to its frequent occurrence as a marker of the rare or exotic.

I suggest here that the manipulation of colour may also relate to deliberate artificiality, exoticism and rarity; concepts which are of direct relevance to an understanding of LBA glass, particularly given its suggested links to precious stones. To return to the above discussion red, white and black, so abundant in material culture, are far less common in nature (in the saturated versions in which they are typically associated with human manipulation), at least until they are revealed through human agency. For example, their association with the body: bones, semen, blood and faeces are all to some extent hidden in everyday life. Neither is fire a permanent (everyday) feature of the natural environment, but it *is* one that can be created and manipulated by people. In other words, the coloured materials that are first selected for human manipulation display colours which are less commonly accessible and (in most cases) less prevalent in salient referents, derived from the natural environment. This is not to say that metaphor and association with the natural world are not important, but deliberate artificiality (in the sense of being constructed by humans) and rarity / exoticism do appear to be sought after in colour selection. Black, white and red may also be seen as 'extremes' of colour – the black of charcoal and red of red ochre discussed above are relatively strong and condensed[31] (in modern colour categorisation terms, although these would not include 'black' and 'white' as colours *per se*, saturated). In contrast to most natural environmental colour ranges, then, the use of black, white and red may stand out as a deliberately artificial and deliberately exaggerated

[31] It should be noted that the description of red ochre as 'intense' and 'saturated' is a deliberately subjective viewpoint. Certainly the reds produced in this way are not objectively as bright or intense as some later pigments such as vermilion (see Lambert 1997, 76). There are, however, few instances where circumstances external to human manipulation produce a more intense red than is possible with red ochre, and the visibility of these is limited in scale or occurrence (such as sunsets or blood).

statement. In societies which manipulate a broader colour palette, of course, the red-white-black pattern is augmented by, or exchanged for, the use of other colours. Nonetheless, the importance of limited access and direct human manipulation – and by association, perhaps, provenance, rarity and / or exoticism – may be seen as a central factor in the selection and manipulation of materials, and one which can be accessed through recourse to those materials as long as external references and factors outside the 'universals' are considered.

An example of the way in which external references can affect the preference for particular colours is given by Chapman's (2002, 59 – 63) discussion of the sources of materials found in Eneolithic graves of the 5th millennium BC from the Black Sea Zone, and their possible relation to environmental / natural features. An opposition is noted between the environmental source of yellow and gold from the sun (and therefore the sky) and the object colours derived from mines and surface / outcrop sources. The valued source of azurite from copper mines is diametrically opposed to its environmental sources of sky and water. The wide range of sources for red materials (mines, surface / outcrop sources and water bodies), however, are suggested to vitiate any correlation with the source of fire and blood (Chapman 2002, 63): the hidden aspect of red has been removed in this context. It should be noted in this case that (with the exception of reddish rock outcrops) access to material forms of the colours mentioned is only available through deliberate human action such as mining or panning. Again, those colours deliberately sought out for human manipulation, while they may be related conceptually to visible environmental features, are the ones for which difficulty of access and revealing of 'hidden' materials are marked and recognised by colour.

Studies of Neolithic stone axe production and exchange in the British Isles provide a useful example of a direct link between colour, provenance and value in an archaeological context. Stone from the major sources exploited in the U.K. (such as Great Langdale and Scarfell in Cumbria) were taken from difficult to access and spectacular locations, yet stone with higher tensile strength (and therefore, in a purely functionalist sense, better) was available in more accessible locations and was not as thoroughly exploited or traded (see Bradley and Edmonds 1993). Here, colour and colour contrast marked the provenance of the stone, and while its particular visual properties may have been rendered valuable by the difficulty of accessing them, they also stood as the primary – indeed, one might argue, the only – referent to that value outside the limited areas from which the stone was quarried.

Thus the colour of objects can act as a marker of their source, and those colours or colour combinations which are more difficult to access may be more highly prized than those which are commonly available. Stronger, more 'saturated' colours might also have a wider

appeal as representing a condensed or enriched version of the properties with which a given colour is associated. As noted by Boriç (2002, 39), these factors can also be deliberately manipulated. Of course, there are other influences to be considered in each individual case, and it should be reiterated that certain visual properties such as brightness or reflectivity can also be considered as an aspect of colour.

In the specific case of glass, it is argued in Chapters 4 and 7 that difficulty of production may be more significant than difficulty of access, or exoticism, but even here the link between colour and access is of relevance: the pre-existing scale of values for precious stones in the Late Bronze Age meant that colour, rarity and provenance were already interlinked in material terms. It should also be noted here that glass was produced in a range of colours from an early stage, and these were almost all strong and saturated, as well as exhibiting a certain degree of brilliance (shine).

A final mention must be made of the necessity of considering cultural contexts in assessing the perception of colour and related properties. The appeal of specific colour attributes, in particular 'brightness', 'shininess' or 'reflectivity' may indeed lend a higher value to materials possessing these properties, but it could also result in negative reactions where a material is known to be relatively abundant, and therefore 'cheap'. Such reactions may be related to the concept of deception: to gain an appreciation of this process one only has to think of the extant description in the English language of shiny, yellowish iron pyrite as 'fool's gold'. An appreciation of these processes is necessary as it is argued in the following chapter that despite the relative abundance of its basic raw materials, glass remained highly valued for several hundred years in Egypt.

Colour and Symbolism

The complex interplay between some of the factors discussed above necessitates a consideration of the way in which colours themselves can take on symbolic meanings divorced at least partially from their material context. Based initially on a study of the acquisition of colour terms and their symbolic associations by blind children, Landau and Gleitman (1985) suggest that the processing of colour information may also depend on knowledge gained via experience. Experiments have also demonstrated that the viewer, on the basis of prior knowledge, expects certain objects to be of a particular colour, and this affects identification of the object colour, so that the visual perception of the viewer is "influenced by his or her prior experiences, knowledge, peer pressure, interest, current thoughts and expectations, thus creating terms of reference" (Muskett 2007, 15).

Furthermore, as approached above with reference to rarity and difficulty of access, colour often serves as a way of condensing meaning, and the meaning of colours is seen to be predominantly culturally constituted (see Sahlins 1976). Boriç (2002, 24) describes the

human perception of colours as a holistic experience, and notes that humans develop a plethora of very conscious meanings associated with particular colours (each of which has a complex cultural significance). The use of colour as a metaphor for emotional states in Anglo-American culture is an example of the way in which colour can consciously be employed metaphorically (Jones and Bradley 1999, 113).

Tilley (1999, 265) notes that while linguistic metaphors signify in an arbitrary fashion, material metaphors are intimately connected with the 'lived world': in this case the colour of objects and materials can be used metaphorically as a mode for revealing unities between the properties of things. This theme is relevant to the ideas discussed above, as colour can unite the value of what is hidden, but can also be related – perhaps symbolically – to wider salient references, in particular to the natural environment.

It is further suggested here, however, that the symbolic associations of colour are not always consciously considered. Certainly, there are occasions when the use of a particular colour carries overt symbolic meaning and indeed the same can be argued for modern society. Colour, however, is a ubiquitous feature of the world around us, often embedded in the meanings and definitions of materials and material culture itself. To what extent these associations are deliberately emphasised with the choice of a particular colour is difficult to assess. Nonetheless, choices had to be made and where these can be identified they prove most illuminating in studying the perceptions and manipulation of the material world.

To What Extent can we employ a Paradigm for Colour Studies in Glass?

The material presented above is intended to provide a theoretical background to the discussion of colour use in Late Bronze Age glass. Certainly, as will be demonstrated in the following chapters, colour played a vital role in the perception and consequent development of glass and glassmaking technology. But to what extent can the diverse examples presented above apply to the Late Bronze Age, and to the specific regions under discussion?

I do not claim that there can - or should - be any rigid universals in archaeological investigations of colour or, for that matter, in archaeological investigation as a whole. As demonstrated above, however, previous work has highlighted the types of question that analysis of colour can be used to answer, and that some aspects of these can be broadly similar across cultural divides. Another key point is that the classification, perception and manipulation of colour do not always follow what might seem a 'common sense' approach to the modern mind. Similarly, 'universal' categories may apply to a number of examples, but they can almost always be influenced and modified by cultural factors. The themes

presented above are developed in Chapter 4 with specific relation to the study of LBA glass, and the broader issues of how to approach the archaeology and materiality of colour are returned to in Chapter 7. For now it should be noted that perhaps the best way of approaching this complex set of considerations is to accept that there exists a range of foci around which colour categorisation, value and symbolism tend to cluster, but that departure from these is also possible. Context, in every sense of the word, is crucial.

4. Colour, Perception and Value

4.a. The Place of Glass

"Colour is more easily painted than talked about."
John Baines 1985

The creation of glass demanded from the start an empirical understanding of a range of complex technological processes and the addition of numerous ingredients from potentially diverse sources. As such, the scientific approach to the evidence in Chapters 5 and 6 has been undertaken with the examination of production processes and issues of technological choice in mind, as well as broader considerations such as (most notably) provenance. But, as noted in Chapter 1, there is another side to understanding ancient glass: its consumption and use, the 'why' of its production as well as the 'how'.

It is this 'why' which stands as the primary focus of the present chapter. I suggest that much of the previous archaeological research on the topic of ancient glass, and that of the Late Bronze Age in particular, has included a number of unwritten assumptions about the way it was perceived at the time. Perhaps the most prominent of these is the commonly touted idea of glass as an imitation of precious stones (see for example Rehren and Pusch 2005, 1756; Robson 2001, 52; Shortland 2001, 211 – 213; Sciama 1998, 6; Stern 1998, 101; Moorey 1994, 196; Oppenheim 1970). It is suggested in the present chapter that this is a misinterpretation of the evidence, stemming largely from the textual descriptions – both in Egypt and Mesopotamia – of glass with relation to lapis lazuli, carnelian, and other stones valued at the time.

I argue that the existence of such descriptions does not automatically assign a lower value to glass[32]. Indeed, it is suggested that in order to grasp the nature and perception of glass during the period of its earliest use in Egypt it is necessary to appeal to one of the key themes of the present work; that of colour, including – as part of its definition – opacity or translucency, and lustre / shine. Thus colour forms the principal – though not the only – material property of glass around which the discussions and ideas presented in this chapter are themed. As with the rest of this thesis, the main focus is Egyptian material from the

[32] During the course of researching and writing the present work Susan Sherratt (2008) has brought the same issue to attention, specifically noting the derogatory connotations of the term 'imitation' and their effect on our understanding of motives and perceptions of the material during the Late Bronze Age. In a previous publication Sherratt and Sherratt (2000, 19) referred to glass as a 'high tech substitute' for lapis lazuli. This is a less loaded description, perhaps, but it is suggested here that even the term 'substitute' does not correctly describe the relationship between glass and semi-precious stones.

15th to the 13th centuries B.C., though some other evidence is considered where it provides an interesting or useful contrast.

The present chapter begins with a consideration of the relative quantities of different colours of glass on surviving objects. It is inferred that a hierarchy of colours may have existed within glass, with some being more highly prized than others, though this hierarchy does not necessarily extend beyond the boundaries of the material itself.

Following this is a discussion of Egyptian views on both colour and precious stones, with particular reference to glass. Here, the importance of language becomes apparent and the reader is referred back to the initial discussion of this with relation to colour, in Chapter 3. The symbolic associations of colour, and the divine associations of precious stones are then outlined, and both are relevant to the ideas presented in the rest of this chapter. The associations between precious stones and concepts of the divine are considered, as is their centrality to Egyptian colour symbolism (the terms for which are often related to precious stones). The status of glass as the product of an emergent technology is also considered.

An assessment of the relative value of glass, i.e. its value by comparison with other materials of the time, is then provided. The value of glass is compared with that of other, more established, materials used in LBA Egypt. It is argued that glass maintained a higher value than that of its component raw ingredients, and it is suggested that this elevated value was related to the specific material properties of glass.

These properties are then examined more closely, again with reference to related materials: faience, precious stones and metals are all compared with glass. It is argued that aside from colour and lustre, the durability of glass, its hardness, its potential for melting, and its consistency (in marked contrast with faience) all contribute to its value and the maintenance of this. The transformative aspect of glass production is suggested to constitute a form of deliberate artificiality. The designs and colours used on vessels are presented as evidence for exaggeration, rather than imitation, of the visual properties of naturally formed precious stones.

Finally, blue glass is discussed in more detail, as a case study for the treatment of Egyptian glass. A particular focus of this section is the textual evidence which has been used to argue for glass as an imitation of, or substitution for, precious stones. It is suggested that reinterpretation of this evidence is necessary, particularly in light of recent advances in the understanding of Egyptian colour terminology. But it can also be seen that by placing material evidence at the centre of the investigation, an understanding of the status and perception of glasses may be more accessible than by recourse to textual evidence alone.

Division of Glass Colour

A study of 228 Egyptian vessels, vessel fragments and small items from published catalogues and dating from the 15th to the 13th centuries BC was carried out in order to establish patterns in the use of colour. Because the aim of this exercise was to assess not just the range of colours, but also their relative proportions in use, it was decided to focus upon finished items only[33]. A summary of the approaches to describing colour is provided in Chapter 2. The material referred to, its relevant publications and museum numbers are presented in Appendix 2.

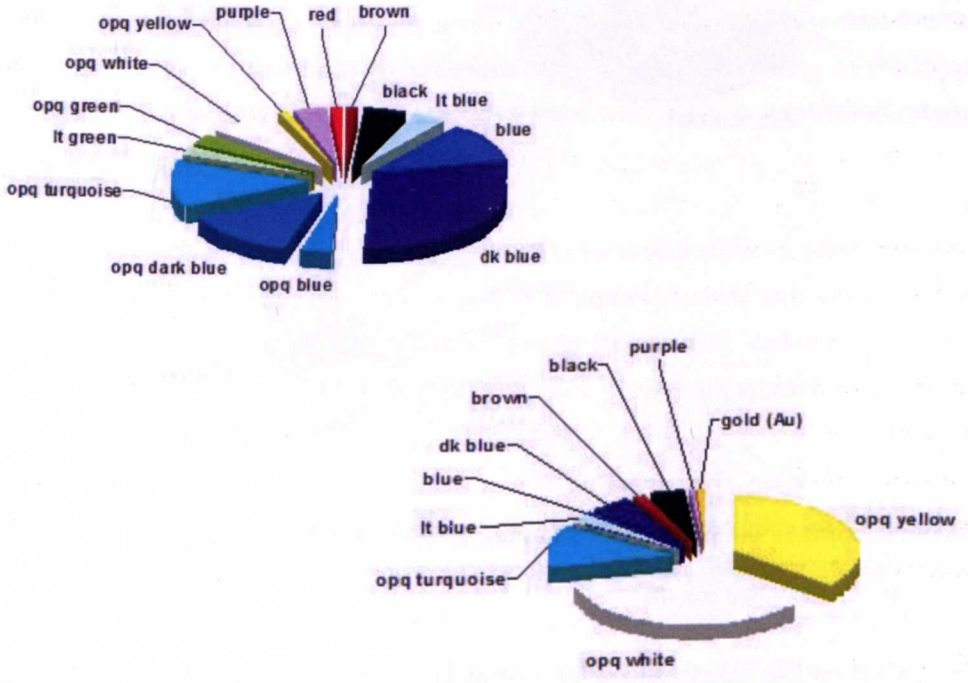


Figure 4.1 Colour Use in Vessels of the XVIII and XIX Dynasties.
Top: base colours.
Bottom: applied colours.

Some of the key information discussed here is summarised in Figures 4.1 and 4.2. 'Base colours' were defined as those colours which form the initial object onto which further decoration was applied. It should be noted that the majority of items have more than one applied colour, so that the charts shown represent the proportions of all present, though not their relative abundance on a particular item, which is often negligible for applied colours because two or more colours are frequently applied in roughly similar proportions.

As illustrated, blues (including opaque 'turquoise') are predominantly used for the base colours of both small items and vessels. In general, analyses have demonstrated that darker blues can be associated with the use of cobalt (see Chapter 3). The presence of

[33] Care was also taken to include only larger fragments in this study: it was necessary to be able to establish the number of applied colours present on finished items, or a close approximation to this, so smaller fragments or fragments of working debris as found at Amarna, for example, were not included in the survey.

impurities in the raw ingredients of the glass melt can also affect the shade produced. Opaque blues are usually in the light- or mid-blue range. Although not all darker blues are entirely translucent due to their depth of colour or to the remains of core material on the interior of core-formed vessels or beads, they are visually distinct from deliberately opacified blues which can be easily recognised due to their duller surface.

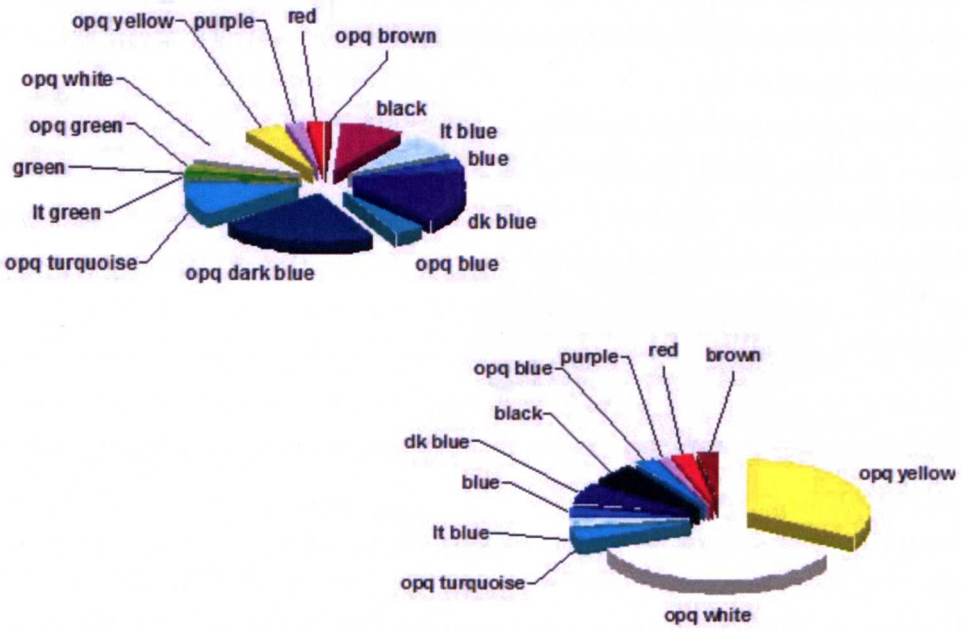


Figure 4.2 Colour Use in Small Items of the XVIII and XIX Dynasties.
Top: base colours.
Bottom: applied colours.

Opaque yellow (the only yellow deliberately and consistently produced in the Late Bronze Age) accounts for almost a third of applied decoration on all the items listed. By comparison it is rarely encountered as a base colour, either on small items or vessels. For vessels, it was found that 73% of those studied featured yellow decoration (the polychrome nature of most vessels accounting for the fact that it only represents a third of the total applied decoration), whereas 34% of small items featured yellow as applied decoration.

Only seven percent of vessels were monochrome. Considering that some known, complete vessels were only decorated on rim and foot, and that even large vessel fragments may thus not have incorporated these, the true proportion is probably somewhat lower[34]. For small items, by contrast, a total of 40% were monochrome, 37% were polychrome, and the remaining 23% bi-chrome. Yellow applied decoration occurs three times more frequently on polychrome small items than on bi-chrome. Only 2 of 124 small items were monochrome yellow. It is possible that yellow decoration was more prized than that in

[34] Further, approximately half of these are dated to the 15th century BC, where some monochrome glass vessels were still produced using lapidary techniques.

certain other colours. Certainly it is more commonly found on vessels, which (using more glass, and being more difficult to produce) were in general more valuable than small items.

The use of opaque white glass is comparable to that of yellow. Sixty seven percent of vessels had opaque white applied decoration, which is almost as many as had yellow. Neither does there seem to be any particular substitution of opaque white for opaque yellow and applied turquoise decoration, or vice versa: yellow and white in particular are generally found in combination, and along with a blue base colour they form the 'typical' vessel from this period. It should be noted that vessels are occasionally described in publication as having an opaque white body when this is in fact an article of corrosion: burial may lead to the formation of opaque white or whitish layers on the surface of a glass (see James and McGovern1996, 145).

It seems that yellow and white glass were utilised to maximum effect as, albeit relatively small, quantities of the two colours were applied to prominent areas such as the rim and base. As they are bright and contrast strongly with the generally darker base colours, yellow and white glass are visually prominent even where only applied in similar or smaller proportions than other colours.

An associated point is that vessels tend to be made with more colours than small items. On average, vessels comprise of just over three colours. It might be argued that a varied range of colours was more desirable once core-formed vessels were commonplace in Egypt; that is once we move into Nolte's (1968) *Weikkreis I*, covering the earliest period of assumed glass production within Egypt, from the reign of Tuthmosis IV. That vessels display more colours than small items may also be associated with the more restricted surface area of the latter, but the increased use of yellow – on over two thirds of vessels – and the greater use of dark (cobalt) blue glass for vessel production, coupled with the aforementioned probable higher status of vessels, suggests that polychromy was a sign of higher status glass objects, and that the dark blue and opaque yellow and perhaps white in particular were of higher value and therefore used on more valuable items. Peltenberg (1971) notes the co-emergence of polychromy in faience and nascent glass technology, and it is possible that the ability to produce a range of colours was a key contributing factor to the impetus behind early glass production.

Red glass is less likely to be combined with other colours and was often used as inlay or for similar functions where it would have been mould-pressed into form (for example, UC 22077, now discoloured, Petrie Museum; EA54925, BM). The technological difficulties associated with the production of red glass may in part account for this, as there was always a danger when heating it that the colour would be lost (see Chapter 3 for more

details on the production technology of red glass). Preservation may also be an issue here as the red glass of the period is susceptible to corrosion and usually develops a thick encrusted layer of green or white corrosion product on its outer surface: the identification of red is thus difficult.

There are numerous other colours of Egyptian glass including green, brown, purple and some examples of almost colourless glass. Where relevant these are discussed in more detail below. Green glass in particular appears to have been more frequently produced as the glass industry became better established so that – from being barely visible in the earliest repertoire of Egyptian glass – it is one of the more frequently encountered colours at Amarna, for example (see Shortland 2000). The volume of green glass produced during the Late Bronze Age, however, never approached that of various shades of blue, nor could green glass rival the frequency and prominence of use of opaque yellow and white glass in decoration.

We might also compare Egypt with other areas. Broadly speaking, the proportions of colour use in Mesopotamia are similar to those in Egypt. At Nuzi, for example, blue was by far the commonest colour for glass finds. What has been described as 'frit' was also found in blue, brick-red, white, black and yellow. Red at Nuzi was very rare. The darker cobalt blue, however, is found less in Mesopotamia than in Egypt. In the Aegean this darker blue is almost ubiquitous among glass finds, and it is generally thought that much of the glass traded into the Aegean – and indeed most of the cobalt-coloured glass – can be traced to an Egyptian source (see Walton et al. 2009; Nicholson et al. 1997).

There is also some apparent change in the use of colour over time. Of the ten or so examples[35] of glass vessels identified to the reign of Tuthmosis III (1479 - 1425 BC) the most common colour was light blue, here including turquoise. One possibly mould-cast opaque turquoise eye-paint container (BM EA 24391) was decorated with gold leaf on its rim, foot and lid. The material from Malkata, where glass was worked (and probably made) under Amenhotep III, is roughly similar in quality, range of colours and style to that from Amarna. At Malkata, however, there is a 'decided preference for a medium blue-green body colour' (Keller 1983, 22) although it is not clear whether the difference in the shades of lighter blues (light blue and medium blue-green) reflects any intentional alteration in the colour end result as all lighter blues seen at the time may have fitted into the conceptual category of a single 'light blue' colour, as discussed below. The change may in any case reflect a difference in production technology, possibly related to the beginnings of primary glass production within Egypt.

[35] The dating of much early glass relies on stylistic evidence only, making it difficult to say for certain how many pieces are known.

A more noticeable change or series of changes can be traced with the appearance and use of darker blue glass. Two thirds of the vessels from the tomb of Tuthmosis III were made with dark, cobalt-coloured blue (Nicholson 2007, 5). This was also the period in which the production of recognisably 'Egyptian' type core-formed vessels began, with the establishment of *krateriskoi* and *amphoriskoi* as the major forms with the characteristic thread decoration in garland and feather patterns of white, yellow and light blue.

The types listed in Nolte's (1968) suggested *Weikkreis* (workshop) series also offer some insight into the development of colour use in the earliest production of core-formed vessels within Egypt. For *Weikkreis I*, roughly 1401 - 1335 BC, the dominant base colours were found to be 'sky blue' (this lighter blue is opaque and could fit into the range of 'turquoise' as discussed here) and dark blue, with threads in white, yellow and blue tones. For *Weikkreis II*, 1391 - 1335 BC, we see predominantly dark blue bodies, followed by bodies of a lighter, 'medium' blue (simply 'blue' in Figures 4.1 and 4.2 above) with yellow, white and light blue / turquoise as applied decoration. There are also rare examples of white, or 'sky blue', glass being used as a base. For *Weikkreis III*, also 1391 - 1335 BC, the dominant body colour is also dark blue, more rarely light blue, with decoration in yellow, white, light blue / turquoise and dark blue.

Colour in Egyptian Thought: the evidence of language, pigments and symbolism

Baines (1985) accepts just four basic colour terms in the Egyptian language: black (*km*); white (*ḥḍ*); 'red' (*dšr*) perhaps more accurately described as warm colours focusing on red; and 'grue' (*w3ḏ*) which refers to green/blue focusing on green. Other terms used to describe colours are also known, though under Baines's classification they are thought of as 'secondary', i.e. referring primarily to an object. These issues are returned to later in the present chapter, with specific reference to the colour blue.

It is worth noting, however, that just as in Egyptian, four basic colour terms have also been claimed in Sumerian and Akkadian (Lansberger 1967). These are as follows: black (Sum.: gi/ Akk.: *ṣalmu*), white (babbar / *pesū*), red (su / sa / *samu*), and grue (sig / *warqu*). Sumerian and Akkadian are unrelated, and the consistency in basic colour terms between them and with Egyptian, suggests Baines (1985, 284), emphasises the primacy of non-linguistic factors in the formation of the set.

During the New Kingdom the increased use of new pigments such as orpiment[36], coupled with innovations in the production of existing pigments (e.g. the use of scrap bronze in

[36] Colinart (2001, 3) argues that the New Kingdom sees the first use of orpiment; Eremin et al. (2004), however, record its sporadic use prior to the XVIII Dynasty; as does Lambert (1997, 80).

Egyptian Blue from the reign of Tuthmosis III onwards) allowed greater flexibility in painting. The 'naturalistic' style of art particularly in vogue during the Amarna period, though with a long history of development prior to this, saw the use of blended colours and a broad palette employing many shades of a variety of hues. Coffins were decorated with a range of pigments, often mixed with one another to produce a specific shade (Eremin et al. 2004, 5). Increasingly intricate designs were also favoured for jewellery and furniture at this time, with composite objects often using a wide variety of materials of different and contrasting colours. All in all, there seems to have been a definable move during the New Kingdom to produce and use as many colours as possible, both in painting and in portable objects and furniture. An increased complexity of design emphasised the use of a number of materials in a single object, usually of contrasting colours. It thus appears that explicit control over colours and the colour environment was deliberately sought after.

Despite issues arising from the separation of colour terms into basic and secondary (and the drawing of subsequent inferences about perception from these) it is widely understood that the Egyptian language demonstrates strong symbolic links for terms relating to colour (not only for the 'basic' terms listed above). This is certainly not uncommon: as noted in Chapter 3, the symbolic associations of colour seem to be present in virtually all cultures. The understanding of Egyptian colour symbolism is apparently quite developed. The following is a consideration of the key points.

As noted by Gillis (2004, 56 – 57), the system of colour symbolism in Pharaonic Egypt seems to have remained fairly static throughout the whole of the Pharaonic period. The Egyptian word for colour (*iwn*) was also used to describe the 'character' of a person, and – as argued by Warburton (2004) – referred to an essential property or quality of a thing, intrinsically associated with it. According to classical religious texts each colour represented its own special value in the Egyptian system of references, capable of 'evoking the idea of divine beauty according to a coded 'language'' (Aufrère 2001, 158).

Colours were often described using terminology derived from minerals, particularly in religious contexts. Yellow was gold, the flesh of the gods; white was silver, which symbolised purity and in some cases is associated with the divine skeleton; pale blue suggested turquoise and recalled the birth space; dark blue was lapis lazuli; green stood for malachite and feldspar and was associated, as were the stones themselves, with vegetation and concepts of resurrection (see Romano 2000, 1606); red stood for carnelian and red jasper, and was associated with evil and blood but also served to protect against these.

As a culture with frequent overt references to the concept of duality (such as Lower and Upper Egypt; male and female) it is hardly surprising that colours in Egyptian society could also be understood in terms of contrasts and pairings. Red and white (and perhaps also yellow) in particular were often conceptually paired (Eaverly 2004, 53) for example in the Eye of Horus.

Ragai (1986, 74) notes that magico-religious ideas were the primary controlling factors behind the use of various pigments and were responsible for the assiduity with which they were sought and prepared. The explicit use of particular colours in specific ritual contexts was associated with deities, and symbolised the triumph of the sacred over the profane. It was thus not simply the rarity of a pigment which gave it value but the mystical powers associated with the colour it imparted. This has been noted, for example, in the decoration of coffins where valuable pigments could be used alongside cheaper ones, choices apparently being made with primary reference to the desired hue and shade over and above the particular value of a colorant (Eremin et al. 2004, 5). The colours of wall paintings were associated with both representation and symbolism, and the complex interplay between the two cannot always be clearly defined.

As argued in Chapter 3, however, it would be a mistake to suppose that symbolism was prevalent in every colour choice. Equally, it should be noted that much of what is currently understood about colour – i.e. the most explicit textual or material references to colours and its symbolism – comes from the evidence of pigment use. Conclusions drawn for pigments do not necessarily apply to glass, but I suggest that certain points arising from consideration of the former are particularly important to the present discussion. These are outlined below.

The existence of so few 'basic' colour terms in a society for which colour and colour variation was so important should set some alarm bells ringing in the Berlin and Kay camp. Considering the wide range of pigments in use, and the practical necessity of referring to these, it is clear that the distinction between 'basic' and secondary colour terms is less significant than may previously have been assumed and that, whatever they symbolised, the sheer range of colours available in pigment form must have precluded thinking about them primarily in terms of whatever the linguistic referents were. Furthermore, the overt symbolism associated with colours in general meant that they were often described, not just in terms of other referents, but specifically in terms of precious stones (the significance of which is discussed below). Viewed in this light, I suggest that the apparent linguistic confusion between glass and precious stones, which has categorised glass as merely an imitation of or substitute for precious stones, was simply an approach to describing the colour of glass. In order to develop this argument, and to gain a better picture of the distinction between glass and precious stones, Egyptian attitudes to the

mineral universe are considered in the following section. A more specific discussion of the terminology used in describing glass, focusing on the most cited example – that of dark 'lapis lazuli' blue – is given in the case study on blue glass at the end of the present chapter.

Egyptian Concepts of the Mineral Universe

Aufrère (2001) provides an overview of the relationship between colour and the mineral universe, in particular with reference to temples: these provide useful foci for a study of Egyptian thought, as they were seen as representing a fully conceived environment, conceptualised but wholly recognisable to the observer. The use of particular materials carried deeper meanings, and their provenance was central to this: for example, control over the desert was evoked through the use of stone quarried from the Libyan and Arabian mountains. No material was devoid of symbolism: the priestly class understood various types of stone to be associated with the titanic struggle between primeval divine forces, and each building stone was related to a particular character type. Clarke (2004, 132) notes that, 'for people living in a world without Kodachrome', colour vocabulary would not necessarily be ordered on the basis of the full spectral range of strong, deep colours: many or most of those hues would only be experienced in especially marked and marginal contexts. As has been amply demonstrated in a number of archaeological case studies (see Chapter 3) the most valued and symbolically potent colours are often those which are the most difficult to access. Saturated, particularly strong colours, are less likely to occur in nature and along with brilliance or lustre this property can be seen as one of the key defining points of value where colour is concerned. The precious stones, inlays, wall painting and funerary equipment of the Egyptian New Kingdom were intended for display in specific – often rarely encountered or in some other way 'special', i.e. limited – contexts, or for consumption and use by specific groups, elevated above most of society. So the specific shade of dark, saturated blue which is associated with lapis lazuli, for example, might only be expected to be encountered in certain contexts, which are not associated with everyday living or salient environmental references.

With this is mind, the relationship between the strong colours of precious stones and minerals and the use of these as referents for the colour(s) of other materials or objects, can be understood as a natural progression from the way the world is perceived and categorised: these 'saturated' colours are rare, and are most prominently associated with precious stones.

The importance of precious stones as a primary referent for other materials is made even clearer when their symbolic and mythical associations are considered. A number of scenes within the mountain temple of Horus at Edfu evoked the bringing of minerals and precious stones, representing the totality of mineral production. Here we see the embodiment of

the idea that the primordial origin of the divine was the Arabian mountains, the source of most minerals (a*Um* VII, VIII). The mineral universe was central to naming and understanding creation and divine works, and materials with the appearance of minerals or metals were also described as, and related to, these concepts. It was believed that the stars took their light from metals and precious stones (Aufrère 2001, 159). Divine powers were related to the ability to perform alchemy and precious stones, as the product of this, were seen as possessing life-giving properties (*Um* 315; a*Um* X). Hathor, the sky goddess, was the inexhaustible container of mineral products (witnessed in the stars). But as well as *providing* precious mineral substances, the gods were thought to extract their powers from them, 'the fluids crystallising in the bowels of the earth' (Aufrère 2001, 160).

By (re-)acquiring minerals and precious stones divine power was further strengthened, and it is important to note that a variety – or 'cocktail' as described by Aufrère – of these minerals and metals was required in order to provide the maximum effect. As with the taste for polychromy in wall paintings, with an increasing palette during the XVIII Dynasty and the use of varied materials in composite objects (see Romano 2000, 1610; Lloyd 1961, 164 - 191), the power of an individual colour or material was insignificant when compared to the power of a range or variety of these.

Whereas the creation of glass has been linked with the 'imitation' of natural stones in a derogatory sense, as a material of presumably lower economic and symbolic value, the analogous references to the 'natural' world within temples are seen as human efforts to honour and mirror the creative abilities of the gods. I suggest that there is no reason why the creation of strong ('saturated') colours using the medium of glass – which allows a true transformation rather than merely surface decoration, as discussed in more detail below – should not be seen in a similar light. The creation of an artificial environment within a temple was not designed to deceive, nor to act as a lower status substitute for the real, external natural world. In the context of a temple, the ability to 'create' or 'recreate' what had been made by the gods is seen as a form of flattery to them, as well as a proof of power and might. The links between strong ('saturated') colours, divine creation and concepts of the mineral universe within temples and in the creation of glass cannot be reduced to what today might be termed as 'pale' imitation. But before these ideas can be explicitly related to concepts of value and the significance of material properties, it is necessary to focus on the place occupied by glass within Egyptian scales of reference.

Glass Production as an Emergent Technology

We might define glass before the modern era as a primarily non-utilitarian[37], artificial material. It was certainly a new material in the period under discussion, and thus may have

[37] It should be noted, however, that definitions of the term 'utilitarian' vary, the narrowest describing only those objects related to physical survival in terms of essential food

been subject to more studied consideration of – and fluctuations in – value, discussed in more detail below. Moorey (2001, 4) refers to a 'courtly motivator' for innovation: aside from military developments, which may be viewed differently, most innovation can be traced to an impetus stemming from centralised control under the ruling elite, and an appeal to aesthetics is a key motivating factor. Indeed, many new human-created materials were first used as luxury / status items. From a variety of contexts these include ornaments and amulets, serving vessels, small vessels used to hold precious oils or cosmetics, and other sorts of 'display' objects such as mirrors and decorative inlays (Miller 2007, 205).

The display function of the earliest glass is apparent in both its use for bodily display (especially in death) with beads and sometimes amulets, and display in public and private spaces such as inlay on furniture and walls, and its use to contain and transport unguents, which can also be related to conspicuous consumption. We may also place the acquisition of glass ingots into a display context where this was referred to in reliefs intended for public viewing.

Materials: substance and form

In order to understand how glass might have been perceived and valued it is also important to consider the ways in which materials and objects in general were classified and understood. During the Late Bronze Age it was raw materials, far more than specific objects, which were the subject of requests in historical records of long distance gift exchange between ruling elites. In the present section I argue that, although clues to understanding the role of glass as a material may also be found in the specific shapes it was worked into, its decoration and contexts of use, it was primarily as a 'raw' material (pre-made, unworked glass) that it was valued and exchanged during the Late Bronze Age.

The primacy of raw materials over objects produced is made evident in textual sources. For example, according to Drenkhahn (2000), Egyptian words for various categories of craftsmen are derived from:

1. Tools
2. Raw Materials
3. Occupations
4. Objects Produced

These are ranked in order of importance. Sandal workers, for example, fit into category 4; potters or brick layers into 3; sculptors, gold workers, painters and metal workers into 1 and 2 (Drenkhahn 2000, 335). The terms used to refer to glass makers and workers in Egypt draw directly from the material being made, such as the use of the term *ḫsbḏ* (see

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procurement, shelter and so on. Broader definitions, however, include those objects perceived as necessary for physical survival: people with spiritual concepts of illness, for example, may have viewed amulets and other ritual objects as being utilitarian (see Miller 2007, 204).

below for discussion of words used with reference to glass), with a range of additional terms to denote rank (the rank may also signify whether we are dealing with glassmakers or glassworkers; see Shortland 2007). Thus glassmaking falls within the range of terms used for higher status craftsmen such as sculptors and gold workers, and it is notable that such higher status craftsmen shared a reference to raw materials, not finished objects, in their titles.

Evaluation of artistic works was restricted to the materials employed. Work could also be assessed in terms of what we might refer to as 'functional adequacy' (Moorey 1994, 15) but not on the basis of its 'artistic' merit. The importance of material over object design or form is also apparent in the Amarna letters, here in an exchange context, as seen in the following extracts from letter EA19 (Moran 1987): 'Still, it [gold] has been worked. But though it has been worked, I rejoiced over it much...' [49 - 53], and 'May my brother send me in very great quantities gold that has not been worked...' [59 - 70]. Considering the potential of gold for reworking and recycling, it is apparent that scrap material held a lower perceived status, at least in the context of long distance trade / gift exchange, again highlighting the primacy of 'raw' materials.

A related point is that, once glass working began to be practiced in Egypt, a distinctly Egyptian style was developed. Several of the earliest (cold-worked) items thought to be imported into Egypt nonetheless bear the cartouche of the pharaoh. Included among these are a turquoise model persea fruit (JdE 61870) and a lotiform cup (MMA 23.9), both inscribed for Tuthmosis III (Lilyquist and Brill 1993, 26)[38]. It seems apparent that, despite the lack of glassmaking knowledge in Egypt, a deliberate 'Egyptianising' of the new, foreign material was practised. The acquisition of glass or glass colorants through tribute or gift exchange may have been important, but there does not appear to have been any desire to highlight the exotic nature of glass in terms of its decorative style.

The subject of exoticism, which can be related to both material and decorative style, also highlights another interesting feature of Egyptian glass production. The opportunity afforded to Egypt in the case of glass, of course, was that the material itself could also be produced locally, and the evidence is that this was done so relatively rapidly (see Chapter 2). Thus the usual arguments about exoticism and colour, discussed in Chapter 3, are somewhat reversed here: it is apparent that the Egyptians wished to display power through the acquisition of and control over a wide range of materials, for which colour was a key defining factor, but it may have been specifically *variety* – rather than exoticism – which

[38] Lilyquist and Brill (1993, 23 – 24) also report composite items with elements of glass, or items with glass inlay, which bear inscriptions of king's names and pre-date Tuthmosis III. Examples include a pectoral with glass inlay naming Ahmose (CG 52004), a plaque naming Ahmose and Amenhotep I (MMA 10.130.170) and an amulet naming Amenhotep I (UC 11894).

was sought (in keeping with the suggestions of Aufrère 2001, discussed above) and which was highlighted through colour.

Restricted access, of course, is another feature here, and the apparent royal monopoly on glass production (discussed further below, with reference to blue glass) must have been a key factor in its status and value. But the value of glass must be explored before we can incorporate it into broader discussions, and the following section provides an overview of those factors which may shed light on this topic.

4.b. Glass and Value

> 'The 'Lord' took residence in it on a sublime dais, he took residence in it on a dais of lapis lazuli, he made it shine with glass and crystal; the lower heaven is of jasper on which are drawn the *lumašu* stars of the gods.'
>
> Akkadian text from Assur (KAR 307) (Oppenheim 1970, 16)

Ascertaining the possible relative value of materials and objects can be a complex process, not least because value can be affected by many factors, can fluctuate over short periods of time and can be viewed differently depending on geographical location, status or group affiliation: value does not necessarily depend on purely 'economic' criteria such as the availability of raw materials or the amount of labour involved in producing an object (see Miller 2007, 213). Thus we might add ritual, social or symbolic associations to factors such as rarity or skill involved in production in examining the criteria upon which value was measured. Colour and other material properties such as hardness often act as the main signifiers of value, and can provide strong signals related to provenance and difficulty of access, as noted in Chapter 3. But for colour in particular – and the term refers not solely to hue but to a combination of visual properties including lustre / shine – it is not easy to define the extent to which it is signifying, and the extent to which it is contributing to value. Equally, cultural factors (such as a previous cultural association of shining metals with wealth) can alter the associations of a particular colour and / or property, provided that the colour itself is not abundant enough in the salient environment to 'dilute' the (visual) reference. Thus, with reference to an example given by Duigan (2004, 80) that gold 'signified beauty *because* it signified preciousness' (i.e. value based on rarity), we should note that gold must be selected from among other rare materials in the first place due to its inherent properties. Not only the rarity of gold, but its shine and malleability, and perhaps even the association between its visual appearance and that of the sun must *all* be considered when discussing its value, whichever period we are studying.

Here I examine the key evidence for the relative value of glass in Egypt from the 15th to the 13th centuries B.C. Sources of evidence for the value of glass are first presented and discussed. It is also suggested on the basis of textual and material evidence that glass cannot be seen as an imitation of, or substitute for, precious stones. Possible reasons for the value of glass are then discussed, and it is suggested that only by recourse to a more fully developed consideration of its specific material properties can its value and status be understood. These material properties are then explored in more detail in the following section of the present chapter.

Evidence for the Relative Value of LBA Glass

In order to examine the value of glass relative to that of other materials, the present section draws on the evidence of both written and material sources.

Annales of Tuthmosis III

Accounts of the Syrian campaigns of Tuthmosis III list gifts presented to the king from Babylonia, Assur and Hatti (see Schlick-Nolte and Lierke 2002, 19 - 21). Shortland (2001) summarises the reliefs, which list 0.73kg of what is translated as 'true lapis lazuli' (*ḫsbḏ m3' dbn 8*) and 2.2kg of what is interpreted as dark blue glass (*ḫsbḏ iri dbn 24*, usually translated as 'man-made lapis lazuli').

A second relief at Karnak records Tuthmosis III dedicating the booty and tributes obtained from his campaigns to Amen-Re. The scene depicts ten registers of gifts, small pictures of the objects themselves along with an indication of the number of the object given and an explanatory text (Shortland 2001, 213). Much discussion has occurred about this scene, as it apparently offers such a wealth of information on the early perception of glass in Egypt. The objects in the top five registers are marked as made of gold (*nbw*), followed by two registers of objects of silver (*ḥḏ*), one of precious stones and then two with objects of copper (*bi3*), so it has been suggested that the objects are placed in order of value (Shortland 2001, 213). Immediately after the objects of silver, and leading the list of precious stones, are five baskets (shown in Figure 4.3) containing round or irregular lumps, originally shown as a blue colour in the first three baskets and a blue/green (or 'turquoise') in the last two. Each basket has an associated line of text as follows (translations from Shortland 2001):

1. {*ḫs*} *bḏ Men-ḫpr R' ḫrtt 24* | 24 lumps of dark blue glass
2. {*ḫ*} *sbḏ m3' dbn 569* | 51.8 kg lapis lazuli
3. {*ḫs*} *bḏ Men-ḫpr R' dbn 600* | >54 kg, <90 kg dark-blue glass
4. *mfkt dbn 93 kt 2* | 8.5 kg turquoise
5. *mft Men-ḫpr R' dbn 10913.8* | 998 kg light blue glass[39]

It is generally agreed that basket 2 contains lapis lazuli (*ḫsbḏ m3'*) and basket 4 contains turquoise (*mfkt*): the use of the phrase *ḫsbḏ m3'* (translated as 'true lapis lazuli', as noted above) in a scene is taken to indicate that the use of *ḫsbḏ* without the qualifier *m3'* refers to dark blue glass (Shortland 2001, 213). Baskets 1, 3 and 5, however, which lack the qualifier *m3'*, all include the royal cartouche *Men-ḫpr-R* ('*menkheperre*'), and Shortland (2001) interprets this as referring to glass, arguing against previous suggestions that the contents of basket 1 represent lapis lazuli. Indeed, the 'lumps' (*ḫrtt*) of material depicted in basket 1 are shown as quite large and very circular by comparison with the irregular shaped objects in baskets 2 and 3, calling to mind the known glass ingots of slightly later contexts in the Late Bronze Age.

[39] The reader is also referred to Nicholson (2007), who contests Shortland's interpretation of the weights.

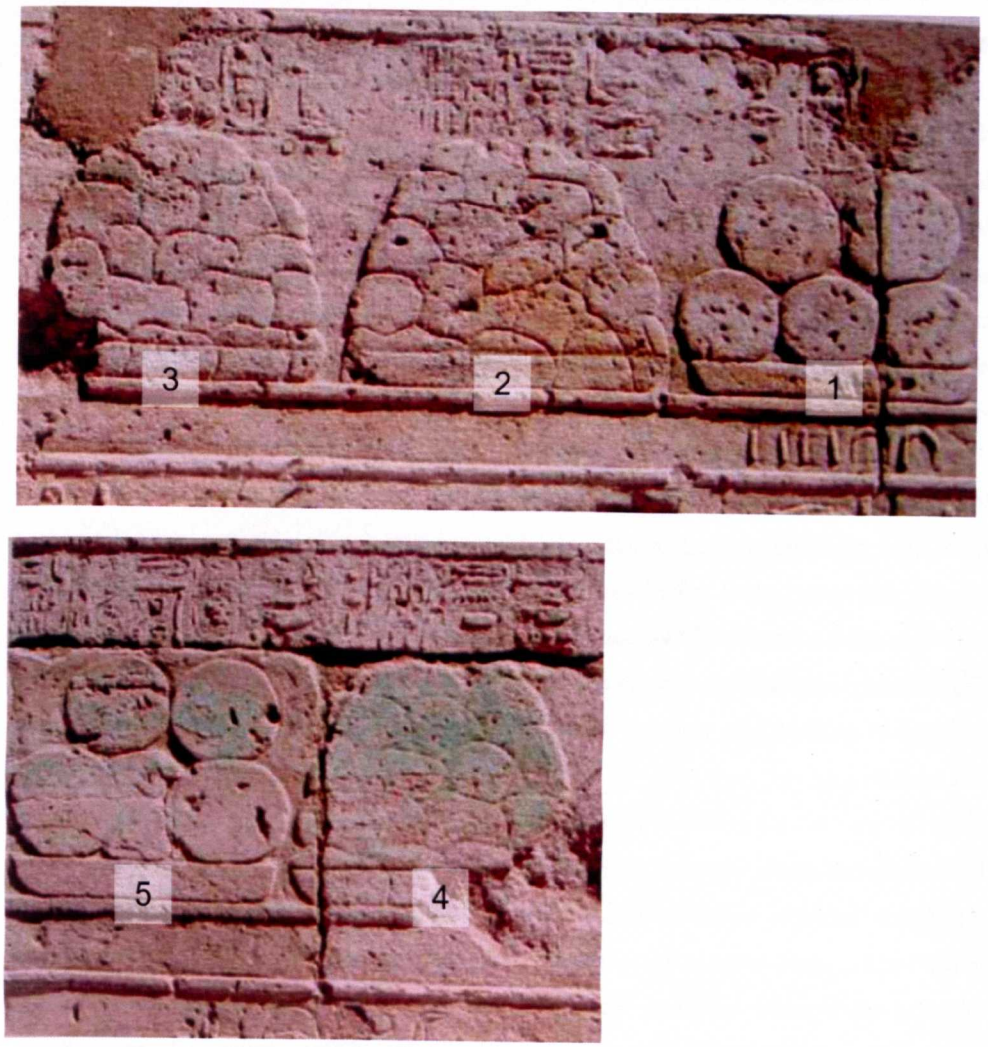

Figure 4.3 Detail from the Annales of Tuthmosis III, Karnak.
The images shown on top and bottom are contiguous, reading right to left.
From Schlick-Nolte and Lierke (2002, 21).

The use of the king's throne name, apparently to distinguish glass from the 'genuine' stone, is intriguing. It certainly suggests a royal connection at this early stage of glass use in Egypt, although the extent to which this continues as glass production within Egypt was established cannot be ascertained on the basis of this evidence alone. In any case, it can be seen that the glass represented in the *Annales* was apparently on a par with the value of precious stones.

The Amarna Letters

Evidence from Amarna may suggest that glass retained this high status into at least the second half of the 14th century B.C. The records of diplomatic correspondence between Egypt, her sister states and vassal kingdoms retrieved from Amarna (see Moran 1987 for English translations), frequently list various materials in the context of gift exchanges or requests, and thus provide a useful means for comparing values between materials although, as with the *Annales* of Tuthmosis III, it is not always directly apparent which

material is being referred to. The letters are for the most part written in Akkadian, the language of international correspondence at this time.

'Glass' (*mekku* or *ehlipakku*) is the subject of at least three letters (EA235+327, EA323, EA331) where it is requested as a 'raw' (unworked) material. This certainly suggests it was important and sought after, though its status as a relatively new material may in part explain why glass was singled out in this fashion (no other letters refer solely to one material). An alternative position is that the terms *mekku* and *ehlipakku* do not refer to glass at all, but to raw ingredients (most probably colorants) used in its production, as suggested by Moorey (1994, 195).

Perhaps of more use in determining relative value are those letters in which 'glass' is listed as a gift along with other materials. As noted above with reference to the *Annales* at Karnak, materials tended to be listed in order of value, the most valuable being first in the list. *Ehlipakku* is listed in EA14 – an inventory of gifts sent from Egypt – and although the first few lines are missing, it is placed directly below an object of gold, and above the vast majority of gold objects, some of which are inlaid (the specific stones used for inlay are not mentioned).

It is suggested here, however, that other references to glass may also be found in the letters. For example, in inventory letter EA13[40] the Akkadian term for lapis lazuli (*uqnū*) is used in isolation, without the addition of the term *kūru*, 'from the kiln' which is usually taken as the signifier of glass. Yet *uqnū šadî*, that is 'lapis lazuli from the mountain' (sometimes translated as 'the genuine stone') is also listed. No *uqnū kūru* is mentioned in the inventory, and neither are the terms *ehlipakku* or *mekku*. It is thus possible that *uqnū* here refers to glass, and that the adjunct 'from the mountain' was used to distinguish lapis lazuli from glass. There is also reference to *muššaru*-stone, sometimes with the adjunct *šadû* and sometimes in isolation, and *šadû pappardilu*-stone[41], suggesting that these are other colours of precious stone which are sometimes used to refer to glass. Furthermore, there does not appear to be any clearly defined distinction in the value of the stones 'from the mountain' and what may be their sisters in glass: the first part of the inventory is entirely given over to the listing of various stones, *šadî* and otherwise, along with gold, which was also used as a mount for the stones according to one or two of the more complete lines of text.

[40] Similar suggestions can be made for terms used in EA14, EA21, EA22, EA25 and EA26.

[41] This stone is mentioned in Amarna letter EA13 and within a Middle Assyrian inventory (*AfO* 18 302 i 7, 8, 12). Oppenheim (1970, 15) notes that it could be brown, red or yellow depending on the context in which its use was described.

If *ehlipakku* and *mekku* did indeed refer to glass, the dedication of specific letters to requests for glass might seem a little strange, given the evidence that primary glass production occurred in Egypt. But the use of other terms such as *uqnū* make sense when we consider glass in its specific context. 'Raw' glass or glass colorants may have been requested by the terms *ehlipakku* and *mekku* (see Oppenheim 1973), but in other instances the important feature of glass was its colour rather than its working properties. In these instances, it is possible to argue that glass could be described in terms of the well-known colours of other stones. This does not necessarily imply confusion or a lower status for glass: perhaps the simplest way to describe the colour of the glass was to refer to it in terms of the precious stone which had the closest colour. Neither was this use of terminology unique to glass: the colours of precious stones were also on occasion used to describe other materials and even features of the natural environment (see Ragai 1986 for examples), as discussed later in the present chapter with reference to blue glass.

If we thus accept that glass was being sent, in corresponding colours to those stones described on occasion as 'from the mountain', it becomes apparent that glass fitted into a similar scale of value as precious stones at this time. No sharp distinctions between the values of the various materials, 'from the mountain' or otherwise, are apparent in the letters. Even in the 'worst case' scenario in terms of finding evidence for the value of glass – that the letters do not refer to it at all – specific demand for *ehlipakku* and *mekku* which may have been vital in the production of glass, or a particular colour of glass[42], implies a very high value for the product which was made from it.

Material Evidence for Relative Value

In order to assess the relative value of glass in the material record, in particular with reference to precious stones, it is necessary to consider glass in a context where it can be associated with other materials. I thus offer the example of inlaid eyes of the XVIII Dynasty, focusing on 'Class II' eyes published by Lucas and Harris (1962). Many of the surviving examples are from the tomb of Tutankhamen, and are now in the Cairo Museum. Table 4.1 shows the provenance of various eyes and their constituent materials. A range of materials were employed in the eyes, the most common being crystalline limestone, obsidian, glass, gold leaf and quartz.

The largest and most consistent use of glass for Class II inlaid eyes is that of the eyelid, where it is the most common material employed (for 53% of those listed above: the remaining 47% includes those where the material used could not be identified). The glass used for this purpose is invariably dark blue in colour, and one might be tempted to suggest it is simply acting as a substitute for lapis lazuli.

[42] It should be noted that the terms *ehlipakku* and *mekku* emerged at the same time as the emergence of glass, providing strong support to the idea that they are related to it in some way (Oppenheim 1973b, 263 - 264).

Eye From:	Eyelids:	White:	Pupil:	Iris:
Anthropoid coffin of Queen Aahhotep	gold	crystalline limestone	obsidian	
Anthropoid coffin of Yuya 1 (innermost)	blue glass	white opaque quartz	obsidian	
Anthropoid coffin of Yuya 2	blue glass	crystalline limestone	obsidian	
Anthropoid coffin of Yuya 3	blue glass	crystalline limestone	obsidian	
Anthropoid coffin of Tutankhamen 1	blue glass	crystalline limestone	obsidian	
Anthropoid coffin of Tutankhamen 2	blue glass	crystalline limestone	obsidian	
Anthropoid coffin of Tutankhamen 3 (outermost)	blue glass	crystalline limestone	obsidian	
Mask of Tutankhamen	lapis lazuli	quartz	obsidian	
Anthropoid Canopic coffins of Tutankhamen	blue glass	unknown	obsidian	
Large Statue of Tutankhamen 1	gold	crystalline limestone	obsidian	
Large Statue of Tutankhamen 2	gold	crystalline limestone	obsidian	
Chariot of Tutankhamen	blue glass	white opaque glass	obsidian	
Canopic jars from 'tomb of Queen Tiy'	blue glass	white opaque glass	black glass	
Anthropoid Coffin of Hat-aai	copper	crystalline limestone	obsidian	
Anthropoid coffin of Queen Meryet-Amun 1	blue glass	Alabaster	obsidian	
Anthropoid coffin of Queen Meryet-Amun 2	blue glass	Alabaster	obsidian	
Anthropoid coffin of Seti I	blue glass	crystalline limestone	obsidian	
Lion's head from throne, tomb of Tutankhamen	unknown	painted	black paint	gold leaf
Lion's head from couch, tomb of Tutankhamen	black glass	painted	black paint	yellow paint
Lion's head from bowcase, tomb of Tutankhamen	unknown	painted	black paint	yellow paint
Leopard's heads, tomb of Tutankhamen	blue glass	painted	black paint	yellow paint
Lion-headed god, tomb of Tutankhamen	unknown		black paint	yellow paint
Ibex, tomb of Tutankhamen	bronze		black paint	brown paint
Cow's head, tomb of Tutankhamen	black glass	white opaque glass	obsidian	
Anubis, tomb of Tutankhamen	gold	crystalline limestone	obsidian	
Cobras, arms of throne, tomb of Tutankhamen	gold leaf	colourless glass	black paint	
Cobras, back of throne, tomb of Tutankhamen			painted	yellowish calcite
Cobra, on stand, tomb of Tutankhamen		colourless glass	painted black	red paint
Serpent standards, tomb of Tutankhamen		colourless glass	painted black	brown paint
Inlaid eyes of horse blinkers, tomb of Tutankhamen	blue glass	crystalline limestone	obsidian	

Table 4.1 Combinations of Materials in Inlaid Eyes of the Late XVIII – XIX Dynasties.

Examples are taken from Lucas and Harris (1962).

Lapis lazuli, however, was only encountered in one instance, in the mask of Tutankhamen along with quartz whites and obsidian pupils. Obsidian pupils were otherwise associated with glass eyes, and none of these materials were strongly associated with painted elements.

Furthermore, gold appears to have been the next most frequently employed material for these high status inlaid eyes. Interestingly, in terms of the so-called 'imitative' properties of glass, the use of gold and blue glass for the same purpose sees less a focus on matching the precise hue in the eyelid than on the specific value of the material itself. Thus, when it comes to selecting the material itself there is no distinction between glass and gold, which are both used with the same additional inlay materials, and no real comparison possible between glass and lapis lazuli, as the latter is extremely rarely employed for this purpose[43]. In contrast, the painted eyes or painted elements of composite eyes *do* tend to match the hue of the materials which are otherwise used in the same elements, and these may thus reasonably be said to be representative or substitutional.

Copper is also used in two eyelids, but it should be noted that one of these is a painted eye, which glass is generally not associated with. Although colour does not seem to have been the primary consideration in selection of materials for eyelids (blue glass and gold being used apparently interchangeably) the predominant use of dark blue glass for this purpose may indicate a hierarchy within glass colours. Similarly, the use of white glass and rare colourless glass in other parts of inlaid eyes corresponds to the suggestions made previously about the elevated value of these particular colours of glass.

Significantly for our arguments against the idea of glass as a 'substitute' for other materials, yellow glass is not found in place of gold on the eyelids. And though black glass was found in two eyelids, it was not found as a substitute for obsidian in the pupils.

A similar illustration of the use of glass alongside precious stones also comes from the tomb of Tutankhamen, in the choice of inlays for his death mask. The mask is made of solid gold and is inlaid with a number of precious stones, including lapis lazuli and carnelian. Horizontal bands of dark blue glass (often rather confusingly described as 'glass paste', perhaps referring to the production process involved in enamelling) are set into the headdress, and their placing alongside gold and precious stones suggests that glass, as noted by Sherratt (2008), appears to be used along with precious stones within a 'broad parity of value'. It is apparent that a larger volume of glass was used in the headdress by comparison with precious stones, and the larger sizes of the enamelled glass, compared to

[43] The rarity of lapis lazuli for this use corresponds to the general lack of finds of lapis lazuli from this period, in part deriving from the practice of recycling (see Moorey 1994, 90).

the inlaid precious stones, are consistent with the relative availability of glass and, perhaps more significantly, the size of pieces of glass available for working. But there is no direct indication that glass was being used as a material to imitate or substitute for others. I suggest, rather, that the mask reflects the New Kingdom preoccupation with the power and value of combinations of coloured materials, as discussed above. It is also significant that glass, along with gold, occupies one of the most prominent parts of the mask, something which we would not expect if it was primarily seen as a lower value substitute.

Evidence for the XIX Dynasty is more difficult to gauge, in part because that for the XVIII Dynasty stems largely from the exceptional wealth of textual and material evidence from Amarna and the tomb of Tutankhamen, both of which are rare instances of material little disturbed by later activity. Nonetheless there are indications that glass continued to be very highly valued well into the XIX Dynasty, such as references to the status of glass workers discussed by Shortland (2007), and the imperial associations of the glass production site at Qantir, which at the least indicate a continued royal interest, if not a full scale monopoly. Perhaps it is significant, in terms of colour, that at Qantir the production of the notoriously difficult to make and work red glass was practiced, whereas at the non-royal, and possibly somewhat later (see Chapter 2) site of Lisht there is possible evidence for the recycling of glass objects and a certain degree of 'muddying' (Mass et al. 2002, 76), or 'tinging' (Keller 1983, 26) of the colours.

We may certainly accept that glass was a high status material. Although little evidence remains to suggest precisely who constituted the spectrum of its primary consumers, the contexts of evidence for glass *use* also point to a royal association, which might also include those of very high status such as priests. These contexts include glass vessel fragments from the palace dumps at Amarna (see Chapter 2), the lack of glass – by contrast with faience – from the poorer areas of Amarna (see Shortland et al. 2001) and the extensive glass finds from royally furnished tombs. The author is not aware of any existing evidence relating to the widespread use of glass by the rising middle classes, though it should be noted that beads tend to be somewhat more physically and socially mobile than, for example, vessels and inlay.

But within this broader context of use there must be a finer definition for the place of glass within scales of value. The combination of textual and material evidence discussed above illustrates that glass occupied a position very close to, if not indivisible from, that of precious stones in the Egyptian system of values, but it has also provided some suggestions that glass was perceived as a distinct material to these. I argue that the evidence presented above places glass slightly below gold and silver and roughly equal to precious stones, finer distinctions being related to the stones, of which some were more highly valued than others.

What Made Glass Valuable?

In order for luxury, display materials to maintain value there must be some restriction of access to these. This is most commonly witnessed through the rarity of the materials themselves or the difficulty of procuring them, as noted in Chapter 3. In some cases such as, arguably, early instances of the use of meteoric iron (see Sherratt 2000, 89), the very rarity of a material might be enough to establish its value as a curiosity. For more enduring examples of value, however, it is pertinent to search for some property in the valuable material which renders it such, and which makes the difficulty of accessing it, and its consequent expense, worthwhile.

In order to understand how particular properties of glass, the production of which was under royal control in Egypt, were able to elevate its value from that of the raw ingredients used in its production, it is first necessary to define what proportion of its economic value derived from the basic costs of raw materials and production processes. This can be referred to as its 'expected value' (see Miller 2007, 213).

The following factors may be reasonably assumed to have contributed to the cost of glass production:

- Raw materials (abundance and availability)
- Fuel and furnace materials
- Skill involved in production

Given the relative abundance of the ingredients require for making a 'raw', uncoloured glass (sand or pebbles, plant ashes) these are unlikely to have conferred an elevated value on the material itself. On the other hand, the materials required for furnace building, and – more significantly – the fuel required for heating provide one method of assessing the relative cost of production.

The experimental reproduction of Kiln 3 at Amarna, mentioned in Chapter 2, provides some indication of the possible fuel consumption involved. Given that the kiln has been considered rather large for primary glass production (see Nicholson and Jackson 2007, 83), the fuel consumption recorded in the experiment may be taken as an 'upper' limit: if smaller, pit furnaces were used (as has been suggested by Rehren et al 1998, 227 - 250) it might be expected that rather less fuel would be required. In fact, the amount of fuel required in the experiment was 'surprisingly small': Jackson (1998, 21) records the use of a total of 380kg of fuel (palm rib, pine and eucalyptus), attaining temperatures of up to 1100°C. The vitrification of ceramic materials associated with glass production at Qantir (Rehren and Pusch 2005) has demonstrated that glass was probably fused at around 1000°C or slightly higher, here from pre-prepared frit (800°C). Given that the sub-structure (though not necessarily the super-structure) of furnaces could be re-used, the furnace-building materials themselves would not have added enormously to the cost. If

smaller pit furnaces were used the costs would be lower still, though there is as yet no way of ascertaining the amount of glass which may have been produced in these. Jackson's (1998) experiment produced one glass ingot of a comparable size to those known from the Ulu Burun wreck, but given that a total of four crucibles were included (two of which failed; one of which contained modern glass cullet) it is apparent that the total amount of glass produced using 380kg of raw fuel could be in the region of a minimum of 9.2kg (assuming the production of four crucibles of glass and based on the size of the Ulu Burun ingots as Jackson does not provide dimensions or weights). The temperatures suggested by Rehren and Pusch (2005) and Jackson (1998) are consistent with those required for copper smelting (c.1120°C). Merkel (1990, 86 – 87) found that between 20 and 50kg of charcoal is required to produce 1kg of copper in experimental reproduction of Bronze Age practices based on evidence from Timna, Israel. Reducing raw materials to charcoal generally results in the loss of c.25% of the original weight (see Henderson 2000, 229). A comparison between the weights of fuel and of resultant 'raw' material between copper and glass can thus be made: c.41kg or between 25kg and 62.5kg of raw fuel would provide 1kg of glass or metallic copper respectively. The production costs of the two are thus directly comparable. Based on this, it is apparent that the elevated value of glass (according to the evidence above, it was of higher value than copper which in any case demands more effort to procure[44]) cannot be due to its raw material, furnace building or temperature requirements alone.

We might also refer to the skill of the glass makers themselves. Shortland (2007, 272) suggests that glassmaking was 'controlled by members of the élite skilled in the ritual and divination techniques of their day'. From a purely technological point of view, the skill of glass makers would to a large extent be related to the ability to successfully colour glass (see Chapter 3), and the acquisition of glass colorants may have been one of the areas in which the raw ingredients were more costly. Even where the sources of raw materials for coloration and / or opacity can be relatively confidently traced, however, discerning the relative cost is not straightforward: certain materials may be difficult to obtain *per se* (by being sourced from a difficult to access or distant place, for example), but have a relatively low 'cost' as they are obtained along with others of higher value, or as by-products in other production processes. In later periods it seems that glassmakers made do with the by-products of other industries (see for example Mass et al. 1998; 1997 on the use of antimonial litharge, a by-product of silver-smelting[45], in Roman glass production), and

[44] Copper must be extracted from its ores which are only found in specific, limited locations, whereas glass can be produced from much more widely available raw materials.
[45] It should be noted that the suggestions of Mass et al. (2002), that yellow glass of the second millennium B.C. was also coloured and opacified with antimonial litharge, mentioned in Chapter 3, have been argued against very convincingly by others (see for example Rehren 2003 and Shortland 2003). The case for using litharge to colour glass during the Roman period, however, is far better established (Mass et al. 1998; Mass et al. 1997).

we may be seeing the beginnings of this with the evidence for glass production at Qantir. The copper used to create blue glass may also have been obtained through the use of bronze scrap (see Chapter 3). On the other hand cobalt and antimony, required to produce dark blue, yellow and white glass, may well have been obtained specifically for glass production, and in Chapter 6 it is suggested that ingredients for glass production were not necessarily obtained from the same sources as those for the production or colouring of other materials. And even where these ingredients were acquired for other uses as well – such as lead for kohl – their addition to the glass batch required the sacrifice of a quantity of the material rather than making use of the by-products of another process.

On the other hand, the probable use of some of the same colorants in faience production, and the widespread use of copper as a glass colorant, suggests that the expense of obtaining these alone cannot account for the relative value of the final product. It is quite probable that the cost of certain colorants is related to scales of value *within* glass, but these alone cannot explain the elevated value of glass[46], though they may have gone some way to enhancing – and maintaining – its royal connections.

Thus a primary economic factor distinguishing glass production from other processes may indeed have been the investment in skill involved in making it. The ability to produce various different colours of glass from the available raw materials must be seen as more significant than the acquisition of the colorants themselves, though it is equally apparent that the necessity to acquire them may have strengthened the bonds between glass production and royal control. But if the skills and secrets of glass makers were the key differentiating factors in glass value, how was the perception of glass affected? We might equally turn this question around and ask, in what way did the perception of glass as a material justify the expense and (probable) secrecy involved in its production? I suggest that one method of addressing these questions is by recourse to the material properties of glass themselves. This is explored in the following section.

[46] As is noted below, however, most faience would use far less of a particular colorant material than glass, as it is only the surface of a faience object which is coloured. In economic terms this may have made some difference to the expense involved in both industries, but it seems unlikely that the difference could have been great enough to count significantly towards the higher value of glass.

4.c. The Significance of the Material Properties of Glass

> "Craftsmen utilised the properties of glass to imitate, order and probably improve upon the designs of nature."
>
> Vandiver (1983)

The basic material properties immediately recognisable in glass may be summarised as follows: colour (including hue and saturation, translucency or opacity, lustre or brilliance), consistency and hardness. In addition, though less immediately apparent, once it has been made (fused from raw ingredients) glass can be melted – at lower temperatures than those required for primary production – and can be worked while hot. It is also, when containing sufficient lime (see Chapter 3), a highly durable material.

Glass is first considered here on the basis of those properties which are most commonly associated with the properties of stone: hardness, durability and consistency. For the latter, a conceptual difference between glass and faience is suggested. Glass is then considered as a transformative material, and the melting and working properties of glass – which may have linked it conceptually to metals – are considered with relation to the degree of visibility of glass production. It is argued that, while the specific processes of glass production were shrouded in secrecy, the fact that glass could be melted and worked while hot was relatively widely understood.

Finally glass is discussed as a material in its own right. It is suggested that glass, whether in ingot form or as a finished (worked) object, was seen on similar terms to precious stones, but that the ability of glass to be melted and the deliberate distinctions between glass and stone most apparent in vessel design meant that its artificiality (as a man-made product) far from requiring 'deception' in terms of imitation, was deliberately highlighted and was therefore perceived as a desirable property.

The Significance of Hardness, Durability and Consistency

Soda-lime-silica glass registers at approximately 5.5 on the Moh's scale of hardness, the same approximate value as lapis lazuli. The Moh's values for other stones in use at the time are as follows: steatite 3; serpentine 4; obsidian 5.5; agate 6.5; garnet 6.5; amethyst 7; carnelian 7; chert 7; flint 7; quartz 7. Values may differ slightly, as not all varieties of stone are the same, but it is apparent that the hardness of glass was compatible with that of those stones most commonly selected for working into various objects. Certainly the hardness of stone was understood and relevant to its categorisation, especially where cold

working was employed as would have been the case for earlier examples of glass in particular. For example, it has been noted that in Mesopotamia, the stones favoured for the production of cylinder seals demonstrate an increase in hardness over time, a possible reflection of attempts by the elite to stay ahead of lower status copying as working harder stones required increased investment. Significantly, for the Old Babylonian (c.2000 – 1600 B.C.) and Kassite (c.1600 – 1000 B.C.) periods stones of Mohs hardness 4 – 6 were preferred (Moorey 1994, 74). Clearly, glass fitted into the appropriate category for this time and its hardness was consistent with that of precious stones.

Another property of glass which is rarely remarked upon, but which may have appealed to the Egyptian system of values was its durability. This was rooted in Egyptian attitudes for existing materials. For example, the durability of gold – that it neither tarnishes nor discolours over time – was a factor in its perception: gold was seen as an 'immortal' substance, related to the flesh of the gods (Romano 2000, 1605).

Durability has been studied in broader archaeological contexts. Miller (2007, 225) notes that the meaning of objects is closely bound up in their temporal connection to people. In a modern setting, for example, we may expect transient objects to be made of plastic, while objects meant to endure would be made of stone (Jones 2004, 335). Thus durability does not simply relate to function but is a socially meaningful quality of artefacts, since it determines how artefacts are valued, used and exchanged.

Most stones, of course, are highly durable, but even here there is an example where this property affected the value and perception of a precious stone: Egyptian references to 'new' turquoise are probably related to the tendency of certain varieties of the stone to become discoloured upon too much exposure to heat and light (see Moorey 1994, 101). Colour, and colour contrast were thus key factors in recognising the most durable, and most valuable, varieties of stone, illustrating the importance of colour in particular as a signifier of other material properties.

We may also witness appeals to durability in the choice of pigments used for wall decoration and funerary equipment (in particular coffins) in ancient Egypt. Ragai (1986, 77) suggests that the impetus behind the production of the pigment Egyptian Blue may have been related to the desire for a more chemically resistant pigment than azurite (a basic copper carbonate) coupled with the stronger (more saturated and brighter) colour obtained with Egyptian Blue (lapis lazuli does not produce a bright colour when ground and used as a pigment, which may explain why it was not used in this way).

Perhaps related to durability is the property of consistency. Here a slight departure from the above approach is taken, and a comparison between glass and faience is introduced as

a means of illustrating the importance of these two material properties (durability and consistency).

Archaeological classification of glass and faience has swung back and forth over time, largely due to the differences between various types of faience and the ambiguities of the term itself. Perhaps the worst terminological ambiguities are those which refer to 'glass paste' as it is often impossible to know whether true glass, vitreous faience, faience or frit is being referred to. Scientific categorisation of glass and faience under the broader heading of 'vitreous materials', however, can be equally misleading for while it is acknowledged that faience possesses a glassy phase, and that the raw ingredients of the two are often very similar, the umbrella term 'vitreous' tends to extend past the boundaries of archaeological science and seep into our understanding of the way these materials were categorised when first produced. I suggest that there are several key differences between glass and faience which render the term 'vitreous' unhelpful in trying to ascertain ancient attitudes to production techniques or categorisation.

Perhaps the most important of these differences seems obvious, but is often overlooked from non-materials science based perspectives, as objects can generally only be described in terms of their surface appearance unless questions of production technology or provenance are under investigation: faience is only glazed on the surface. This has important connotations for the perception of faience and glass, and for our understanding of how colour and colouring was valued.

The constancy of glass as a material marks it from faience. Although surface properties such as lustre and colour are undoubtedly important to aesthetic responses, signals are also affected by historical-relational facts about objects and materials (Currie 2004, 228 – 229). Like the gold-plated wooden statues sent to Tiye, described in Amarna letter EA26 where a furious complaint is issued that statues of solid gold had been promised, faience presented what may be termed as a 'deceptive' surface appearance (albeit a more acceptable one as faience was a material which had been consistently made and used for a long period of time). But although 'deceptive' or 'surface' appearance was an accepted property of faience objects, it must have affected their value. It has been noted previously in the present chapter that raw materials – often transported in bulk – were more significant than finished items, despite what is often thought of as the added value input of workmanship. In certain other recorded cases of gift exchange, the covering of one precious material with another is explicitly described. For example in Amarna letter EA22 (see also EA25), two 'leather' *uḫatati* are described as overlaid with gold and silver, yet 'their centre is made of lapis lazuli' (which could equally refer to glass on the basis of the arguments presented above), and a hand bracelet of iron (then a valuable substance) is also

listed as covered with gold[47]. Both the care of the descriptions and the existence of such objects themselves suggest that covering one substance with another was acceptable and of value as long as the material inside was also valuable: they make it clear that surface appearance alone was not enough to define the properties of an object. The materials themselves remained conceptually separate and were described as such (and there are frequent references to 'solid gold'), whether or not the covering of one material with another was visible. By contrast, if faience was scratched or broken, the crumbly and discoloured material beneath the lustrous surface would be revealed: not a covering of one valuable material with another, but a thin surface veneer over a body lacking in specific definition, value or symbolic meaning. There could be no such thing as 'solid faience'. On the other hand, break glass, chip it, melt it and work it and it remains constant in colour, texture and material throughout[48]. Furthermore, since there is no such thing as 'solid' faience, it could *only* be traded in finished form and thus – unlike glass – could not join the privileged ranks of those materials which could be traded in raw, bulk form and thus seen to possess intrinsic value.

Nonetheless, the inception of glass production clearly had an impact on faience. As noted above, the relatively sudden appearance of glass in a range of colours is complemented by a sudden expansion of the range of colours in faience: yellow, intense blue, indigo and violet all appear in faience during the XVIII Dynasty (Moorey 1994, 185). Similarly, glass seems to have affected the types of faience produced, and the first production of so-called 'glassy' or 'vitreous' faience (faience with a thicker, more significant glassy phase) is roughly coincident with the introduction of glass (see Lilyquist and Brill 1993). Distributional evidence from Amarna has illustrated the difference in value between glass and faience, and the tighter royal control over the former (Shortland et al. 2001) but the attempt by faience workers to replicate to some extent the consistency of glass suggests that this was indeed a highly desirable property. It may in part have stemmed from an attempt to reproduce the visual properties of glass with respect to light: certainly the thicker the glaze on faience, the more lustrous the item appears to be. It has also been

[47] The letter was sent from Tushratta, king of Mitanni, to Amenhotep. The bracelet is described as 'a hand bracelet of iron, overlaid with gold: its *mesukku*-birds have an inlay of lapis lazuli from the mountain. Five shekels of gold have been used on it.' It is worth noting that the weight of the gold used is listed here: the primacy of raw material value is prevalent even in the sending of preformed items of jewellery. The placing of the bracelet high in the list, as well as explicit mention of its iron core may suggest that the use of iron was a positive attribute, despite the fact that it is covered with gold. No weights are given for the iron, but this is perhaps unsurprising considering its rare, almost 'novelty' status. We should not overlook the possible symbolic attributes of a bracelet containing a core of what was at the time a rare material, acquired only in its native form from a limited number of sources.

[48] Interestingly, one instance where form and surface appearance seems to have been equally, if not more important than material was in the creation of amulets. As noted by Andrews (1994) the potency of amulets was thought to derive at least 50% from their form, and it is in the specific case of amulets which faience – easily moulded and possessing colour and shine on the surface only – outstrips glass in popularity and variety.

suggested that this was related to the availability of a certain amount of glass cullet for faience production (Welham et al. 2003, 13), but evidence for the use of different materials in glass and faience production (see Tite et al. 2002) suggests that, if this did occur, it was by no means the normal practice. Whatever the primary inspiration behind this advance in faience technology, however, it is apparent that faience – for all its ability to provide similar visual effects – was a very different material to glass, in terms of production technology, value and perception.

It should be noted at this point that although (as discussed earlier) pigments applied to wall paintings and coffins, etc., provide us with an interesting insight into the symbolism of colour and perhaps the increasing desire for polychromy, they – like faience – are fundamentally different uses of colour to that in glass. As with faience, pigments provide surface colour only. Although their selection may be based on obtaining a particular desired colour, it is clear that the use of gold foil covering for coffins, for example, was nonetheless a more desired medium for the representation of the yellow / gold colour. Furthermore, the most expensive coffins (such as the gold inner sarcophagus of Tutankhamen) were rendered from solid material. As noted earlier in the present chapter, painted elements were rarely combined with expensive materials in inlaid eyes. Those who could afford it may occasionally have chosen to have cheap pigments and materials alongside the more expensive for reasons other than the display of wealth, perhaps associated with the desire for polychromy, for the use and display of a wide variety of materials (as discussed above): the use of a range of materials and substances highlights control over resources and power, but when it comes to the classification of individual materials, those for which surface appearance differed from their 'substance' were less valuable, and in most contexts less magically potent. With reference to the discussion of re-melting (see below) and recycling (Chapter 5), it should also be noted that glass (in particular glass ingots or inlays), like imported 'lumps' of precious stones and metal ingots, could be treated as a 'raw material', so that it maintained a primary value whether or not it was eventually re-worked. This does not have to be related to re-melting of 'scrap' glass, but could relate to the re-working of, for example, a single glass inlay.

An intriguing contemporary comparison may further support these suggestions. Kate Spence (1999) notes the brief resurgence of the use of coloured stone in Egyptian temple architecture during the mid-New Kingdom (c.1473 – 1290), primarily for small shrines. From predynastic times the use of various building materials, minerals and precious stones was carefully considered along with the language of colour in the architectural and decorative schemes of tombs and temples (Aufrère 2001, 158) but prior to the New Kingdom the use of more expensive stones had waned in favour of applied decoration and cheaper, more readily available stones. Spence (1999, 115) suggests that as well as a certain measure of prestige added to the stone through difficulty of obtaining it, the very

durability of stone and the specific colour of the stones selected were important factors in selection and use. Furthermore, the *consistency* of the colouring, in opposition to the superficiality of paint, is thought to have reinforced the potency of colour association in these contexts.

It is interesting to note that this example comes from the very period under consideration with the first use and categorisation of glass, and that coupled with an apparent increase in interest in polychromy and the use of colour in general, there is evidence here of the importance of colour as an intrinsic property of certain materials, illustrating that although surface colour was of interest material itself retained primacy, at least in some applications (notably those of high status or ritual / symbolic importance). In the case of glass, and in the precious stones it was related to, consistency and durability must have been important aspects of value, even if – as with the building stones mentioned here – a part of that value resided in difficulty of access, either controlled or uncontrollable by the ruler.

Re-melting and Transformation

It is difficult to trace the extent to which the processes of glassmaking were known, i.e. to what extent these were understood by those who traded in and 'worked' raw glass, or used finished glass items such as beads and vessels. The use of the Akkadian term *kūru* ('from the kiln') discussed above certainly suggests that, in the distinction between glass and 'natural' stones, glass was recognised as being 'created'. Texts written in Egyptian also follow a similar trend: descriptions of glass as xSbD iri (literally, 'lapis lazuli that is made') illustrates an understanding of its man-made nature in the definition of the material (Shortland 2001, 219). But the degree of awareness of the precise processes involved in its production is more difficult to trace.

Egyptian evidence strongly suggests that various (royally controlled) crafts were practised in close proximity to one another under a complex division of labour: individual craftsmen specialised in the working of specific raw materials but the necessity of supervision and frequent requirements for collaboration, for example in the production of composite items, made close proximity advantageous (see Drenkhahn 2000). The evidence at Amarna suggests that this was the case for glass and faience working. But there is no reason to assume it was also true of glass *making*[49].

[49] The situation in the Near East is more complex. Specialist craft areas existed in some towns, while in others it seems the entire settlement specialised in a particular craft. At Ugarit, a craft quarter for sculptors and fine metalworkers was discovered in the southern part of the city, far away from the palace. At the beginning of the LBA copper smelting at Enkomi, Cyprus, was conducted in a large fortified residence on a northern edge of the town, but was moved elsewhere when a city wall was built enclosing the site. In some cases in Mesopotamia, craftwork took place outside the town, as is evident for the Old Babylonian period at Ur (Matthews 2000, 461).

As with metal production, where smelting is known to have occurred in the highlands of Palestine, Cyprus and Anatolia and the metal was transported in ingot form to be worked, glassmaking may well have taken place outside the normal (central) craft processing areas, or at least in specialised industrial quarters such as the large-scale bronze-working site at Qantir. Texts suggest that metal ores were generally refined close to their sources in the Near East, in wooded areas where sufficient fuel was available to achieve the high temperatures necessary for smelting (Gunter 2000, 1546). Glass production requires similarly large amounts of fuel as noted above, and due to the extreme temperatures involved it too counts as one of those 'anti-social' technological processes which would not be desirable in close proximity to living quarters (see Moorey 1994, 17). Indeed, in numerous later examples of primary glass production see it situated away from other craft processes[50].

It is also possible that glass making was not an ongoing process, and was not necessarily permanently situated. The oft quoted (though more usually with reference to ritual) passage from the Mesopotamian texts, 'when you set up the foundation of a kiln to [make] 'glass', you [first] search in a favourable month for a propitious day...' (Oppenheim et al. 1970, 32 - 33) illustrates that production may have occurred intermittently, or at least (given the possibility that the texts do not refer to glass) that certain manufacturing processes were not permanently situated. In an ethnographic parallel, a study of traditional Indian glass making activities during the 1990s (Sode and Kock 2001) showed glassmaking as occurring sporadically throughout the year, for up to a month at a time: those who made glass did not engage in the activity full time.

There is thus no reason to assume that the precise processes of glassmaking, which in any case are likely to have been shrouded in secrecy, were understood even by those familiar with other craft processes: it is more plausible that glass making was conducted a little away from most of these. Glass working, on the other hand, was probably better known: the proximity of craft workshops to royal centres suggests that glass working would have been a far less secretive, and arguably less specialised process. This specialisation is referred to by Shortland (2007, 272), who argues on the basis of textual evidence that glass workers were of lower status than glass makers.

If primary glass production was situated away from other craft processes, it is possible that the general understanding of glass as 'made' or 'from the kiln' (see above) came as much

[50] Examples include the 4th – 7th century AD great glass slab identified as the remains of a failed glassmaking attempt, found in a cave at Bet She'arim, Israel; the nearby remains of tank furnaces at Hadera; and the remains of large-scale Roman glassworks at Wadi el-Natrun and Alexandria (see Freestone and Gorin-Rosen 1999). European Medieval glassmaking and working took place well away from areas of habitation, and the Venetian glass industry was famously isolated for reasons of both safety and secrecy.

from its working properties as knowledge of primary production. On the other hand, the fact that glass was produced in ingot form, and that – along with the king's throne name – this was chosen to be highlighted in the fifteenth century *Annales* at Karnak, suggests a conceptual link with metals. Similarly, the linguistic evidence points to a deliberate highlighting of the 'made' nature of glass. Just as the smelting of metals involved a transformation from their ore minerals, requiring technological skill and understanding, the presence of glass in ingot form must have implied a degree of transformation.

Ingots also proclaim the 'raw' (un-worked) state of a material, while making it immediately apparent that the material can be re-melted. Considering that this was not the case with stones, it would have been pretty well understood by any encountering ingots in reality or in depictions that they could be melted, and indeed that they had been produced in ingot form already, clearly by some form of human manipulation.

Because glass making, as a transformative process, involves a complete alteration of the materials added, producing what to all intents and purposes was a highly coloured stone (albeit one which could be further transformed through the application of hot working), and bearing in mind the value of many such stones, its realisation has been compared with the aims of the medieval alchemists – to produce a valuable substance from base ingredients (see Sherratt 2008). As mentioned above, I suggest that one of the key differences between glass and faience is consistency: glass *becoming*, rather than imitating, a coloured stone, albeit one that is recognised on the merits of its own properties, in particular that it can be melted.

Transformation imbues an individual or group with control over their environment and constitutes a means by which to communicate that control (Peters 2008, 189). The possibility that glass production occurred in a two-stage process is discussed in following chapters, and this issue is returned to, with relation to transformation, in Chapter 7. For now, however, it is worth noting that coloration and transformation may have strong mutual ties. One interesting aspect of the process of transformation of glass from its raw ingredients is the change in minerals added as colorants: as noted in Chapter 3, the colours of glass could be notably different to those of the ingredients added to the batch melt. The bright pink colour of certain cobalt ores, for example, contrasts sharply with the very deep blue that is produced as a result of their addition to the basic glass mix. Similarly copper ores, generally green, or copper and copper alloy metals can impart a range of blue, green and purplish colours to glass, as well as the signature 'sealing-wax' red produced under reducing conditions.

It is also possible that where quartz pebbles (rather than sand) were the primary ingredient of glass making the links between stone and glass were directly apparent to those aware of

the ingredients. It is also quite probable that a link between sand and stone was understood. So the relationship between glass and its original ingredients may well have been of note, but the specific colour of glass must be a key part of the transformative process of its production, as the potential for colour manipulation was recognised even before the ability of glass to be hot worked was properly utilised. In any case, these two properties of strong coloration (involving transformation from the colours of the original ingredients) and the ability to be hot worked – both of which can be recognised by those not involved in primary production – must have been important for the definition of glass as a category of material. In the following section these arguments are expanded upon as it is suggested that, despite clear links with both metals and precious stones, the nature of glass as a man-made material in its own right was deliberately called to attention.

Exaggeration and the Artificial

Artificial materials are classed as those which have had their basic physical or chemical structure transformed by human action (see Miller 2007, 204 - 206). Such processes often involve a focus on colour. For example, the first known use of fire in technological production includes the roasting of red ochre to brighten and strengthen its colour (Miller 2007, 205). Similarly, the New Kingdom transition to the use of orpiment on funerary artefacts, discussed above with reference to polychromy, allowed a more intense yellow than was possible with the previous use of yellow ochre (see Eremin et al. 2004, 4 - 5). Egyptian Blue and faience also demonstrate existing links between artificiality and strong coloration.

Peters (2008, 195 – 196) draws a distinction between 'natural' and 'inherent' colours, arguing that the rarity of more 'subtle' colours such as pink and orange in Cretan frescoes illustrates a use of colour as a method of deliberately constructing the environment and, crucially, asserting control over surroundings. Thus strong coloration can in some contexts represent an exaggerated form of the natural world, perhaps almost a deliberate artificiality. Certainly the number of colours employed in numerous single items of glass (see above) suggests a fascination with polychromy. In many ways, it might be argued that those precious stones most favoured by the Egyptians (and equally, if not more so, their Mesopotamian neighbours) themselves were of unusual, almost unnatural (in the sense of salient references and the surrounding landscape) colours. Indeed, the use of terms for lapis lazuli and turquoise to refer to the shade of the sky (discussed below) rather than the sky acting as the main reference point for blue colours, demonstrate the importance of the rare over the mundane, the primacy of that which was hidden or difficult to access.

It may be difficult to distinguish technological from symbolic or value-based reasons behind the particular colours popular in glass, but it is worth noting that stronger colours did seem to be favoured over less intense ones. For example, with reference to the study of

colour use presented earlier in this chapter, translucent purple could be produced but is far less frequently encountered than blue(s), green(s), turquoise, yellow or white. As amethyst was a precious stone in use at the time, we cannot assume that the dominant colours of glass were simply those similar to precious stones[51], although the fact that neither amethyst nor purple glass were used to as great an extent as other colours of glass and stone might hint at a common reason behind the lesser popularity of both. In terms of colour, then, we may be seeing deliberate intensity of hue, and exaggeration in the combination of hues on individual pieces.

Figure 4.4 Marbelised Goblet from the Tomb of the Three Foreign Wives of Tuthmosis III.
Made with fused glassy faience. MMA 26.7.1175.
From Lilyquist and Brill (1993, cover).

I also argue that glass vessel design displays a deliberate exaggeration of the natural properties of precious stones, something which was first – albeit briefly – suggested by Pamela Vandiver (1983) with reference to glass from Nuzi. The darker base colours (i.e. colour of the main body to which decoration is further applied; see above) of most glass vessels, with bands of patterning in contrasting colours, recall the contrasting veining in the three most prized precious stones: lapis lazuli, carnelian and turquoise. In all but a few

[51] Neither can we cite technological difficulties as the sole reason behind the lesser use of purple glass, as we might for colourless glass (which when it does occur is usually associated with particularly important items, such as the inlaid eyes in the tomb of Tutankhamen, discussed above). Purple glass is sometimes encountered on amulets, as on the heart amulet sampled for the present study (CUMAA 1932.412) and, rarely, on vessels, but does not appear to have been selected for particularly prestigious uses.

of the earliest examples of glass in Egypt, however, the banding is deliberate, ordered and recognisably different from that found in natural stones.

By contrast, there are few if any examples of attempted 'naturalistic' veining or spotting in the earliest glass. Interestingly, some of the early examples of 'vitreous' vessels in Egypt which have been taken to truly imitate stone in a naturalistic (and consequently in a potentially or intentionally deceptive) sense were in fact made from faience or glassy faience. An example of this is the marbelised goblet (MMA 26.7.1175) from the tomb of the three foreign wives of Tuthmosis III, shown in Figure 4.4. Its naturalistic, random pattern of swirls was created by fusing various colours of vitreous ('glassy') faience (red, off-white, white, turquoise) and is comparable in colour, material and design with fragments known from Nuzi and Susa (see Lilyquist and Brill 1993, 21).

Figure 4.5 Vessel Inscribed for Tuthmosis III.
Yellow and blue glass festoons on a blue body.
From Newberry (1920, Plate XVI).

By contrast, some of the earliest glass vessels known in Egypt show an even more pronounced degree of exaggeration than their later, highly stylised counterparts (the products of a more settled, and probably by now purely Egyptian, industry). For example, a vessel inscribed for Tuthmosis III shows some of the boldest design of any early glass vessels, with thick bands of yellow and dark blue glass applied in large looping festoons over a lighter blue body, as shown in Figure 4.5.

Figure 4.6 Veining in Lapis Lazuli Compared with Trailed-On Decoration in Glass Vessels.

Left: white and gold veining in lapis lazuli. Note the turquoise appearance of the deeper veining.
Centre and right: applied (trailed-on) decoration on glass vessel (see Figure 2.7).
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Figure 4.6 illustrates the most striking comparison between the appearance of glass and precious stones: that between the colours and form of veining found in lapis lazuli (left) with typical decoration encountered in glass vessels (centre and right). As shown the combination of gold- and white-coloured veins in lapis lazuli is very similar to the use of yellow and white applied (trailed) and marvered decoration in glass. Furthermore, the translucency of the lapis lazuli and depth of colour makes some white bands appear light blue, and this (often in the form of opaque turquoise blue) is also a popular colour choice for applied vessel decoration. Veining (and sometimes spotting) is also, though not always, present in other precious stones valued at the time, including turquoise and carnelian as illustrated in Figure 4.7.

Figure 4.7 Examples of Natural Veining in Carnelian and Turquoise.

Left: carnelian.
Right: turquoise.

Thus banding or veining, and spotting, were understood as one of the characteristic features of the stones prized during the Late Bronze Age. Different varieties of precious stone were identified and categorised based on colour and the presence of contrasting colours, as noted in Chapter 3. That contrasting colours were also so important to glass alerts us to the fact that much of what was prized about glass was indeed related to precious stones and symbolic concepts of these. But the regularisation of this banding,

deliberately calling to attention the human manipulation and creation of the objects suggests that glass was not, in this way at least, being made and worked with the deliberate attempt to 'deceive' its consumers into believing it to be something which it was not.

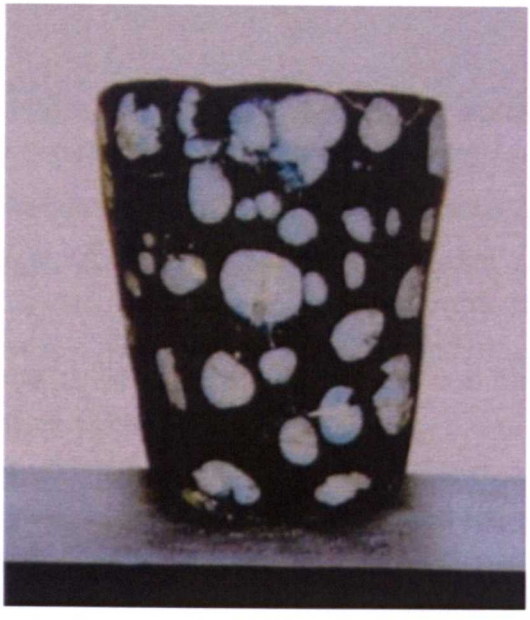

Figure 4.8 Glass Beaker from the Burial of Nesikhons.
Dark brown with white spots.
Cairo Museum (J.26246).
From Schlicke-Nolte and Werthmann (2003, 15).

Although a little later than the period under discussion, an interesting comparison with the earliest vessels produced in glass comes from some of the large set of glass beakers (approximately twenty in all) known from the burial of Nesikhons, wife of the high priest Pinodjem II. The burial is well dated to 975 – 974 B.C. (Schlick-Nolte and Werthmann 2003, 17), though the vessels are now scattered across several museum collections and it is not always easy to be certain of their location. Of those known, however, several display interesting characteristics which may be consistent with attempts to imitate, rather than exaggerate, the properties of stone. One of the beakers from Cairo Museum (J.26247A) is translucent green with slightly swirled yellow lines. It is not entirely apparent whether this is the result of recycling (as may be the case with the lower quality material from Lisht), a deliberate attempt to replicate the random, naturalistic swirls of veining in stones, or a combination of the two. Another beaker (J.26248) has a more characteristic feather pattern over a dark blue base (many of the beakers, in contrast to the use of colour in earlier examples, are opaque yellow), but a further example (J.26246) has a different pattern altogether. This dark brown beaker (shown in Figure 4.8) is decorated with white spots reminiscent of the porphyritic rock frequently selected for grinding and polishing into vases and other vessel forms. A number of vessels from the burial of Nesikhons, and possibly elsewhere, are thought to have displayed matching patterning, although most seem to have been either lost, corroded beyond recognition (and possibly

preservation) or are in storage at Cairo Museum due to their fragile nature (Schlick-Nolte and Wethmann 2003, 20). It is interesting that this form of more 'naturalistic' imitative decoration was rendered in glass at a time when it was not technologically as advanced (in either making – and we may be seeing recycling here – or working) as the earlier industry: it would thus be difficult to argue that the New Kingdom glass was not produced in more 'naturalistic' imitative designs on the basis of lack of technological know-how.

Vessel type	Material	Dates	height (cm)
kohl jar	red and white limestone breccia	1550 – 1525	4.8
Carinated oval dish	glazed steatite	1525 – 1504	3.2
kohl jar	glazed steatite	1525 – 1504	5
squat jar, high neck, raised foot	glazed steatite	1504 – 1492	8.9
kohl jar	glazed steatite	1504 – 1492	5.2
kohl jar	glazed steatite	1504 – 1492	5.2
kohl jar with relief monkey	black serpentinite	1492 – 1479	5.5
composite kohl tube	white veined stone	1479 – 1457	6.5
lotiform cup with integral stand	gold-trimmed (stone not listed)	1479 – 1425	10.5
Ointment jar with lid	gold-trimmed (stone not listed)	1479 – 1425	11.7
Ointment jar with lid	Serpentinite	1479 – 1425	10.8
squat jar, high neck, raised foot, with lid	Anhydrite	1479 – 1425	7.3
squat jar, high neck, raised foot, inscribed lid	gold-trimmed (stone not listed)	1479 – 1425	9.6
piriform jar with lid	hornblende diorite	1479 – 1425	10
piriform jar	Limestone	1479 – 1425	4.5
bottle with high neck, with lid	gold-trimmed (stone not listed)	1479 – 1425	9.8
bottle on raised foot, with lid	gold-trimmed (stone not listed)	1479 – 1425	13.5
kohl jar with lid	hornblende diorite	1479 – 1425	8.4
squat jar, high neck, raised foot	Limestone	1479 – 1401	7.3
squat rounded jar	Limestone	1479 – 1401	4.2
squat jar with high neck and raised foot	not listed - stone, 'quite crystalline'	1427 – 1401	15.1
Canaanite amphoriskos with integral stand[52]	not listed – stone	1427 – 1401	21

Table 4.2 Stone Vessels of the Early XVIII Dynasty and their Heights.
Only vessels with similar forms and uses as those made of glass, and with a known height, have been included.
Constructed using data from Lilyquist (1995).

The size of some early glass vessels might also prove illuminating. Table 4.2 presents a selection of rare intact stone vessels from the earlier part of the XVIII Dynasty. Of the 22 vessels listed, only 2 have heights exceeding 15cm. Both are of an almost translucent, whitish stone which may be alabaster. The more deeply coloured (several of which are spotted or veined in strongly contrasting colours vessels of hornblende and serpentinite are

[52] Included here because it was found to contain traces of ointment and is thus considered among the unguentaria.

all far smaller. 19 of the 22 are less than 12cm in height, although many cluster around the 10cm mark. Little survives of vessels formed from precious stones although other evidence suggests they did exist (see Moorey 1994, 85 - 94) and would have shared similar properties of desirability to other stone vessels in terms of contrasting veining, for example. It is likely that a large amount of objects made from precious stones, and lapis lazuli in particular, were recycled by grinding and forming into different shapes (Moorey 1994, 86 - 91). By studying surviving stone vessels, however, we can at least begin to appreciate the properties and forms which were most prized or at least most common in the full range of stone vessels.

We may compare this with evidence of glass vessels of the same period. From the tomb of Amenhotep II (KV35), dating to c.1400 BC, are 76 glass vessels which Nicholson (2007, 7) notes as being exceptional for their size: the largest is some 40cm in height. Further examples of these large vessels are thought to exist from the time of Amenhotep II, though they have been removed from their context (see Cooney 1976, 143). From the tomb of Thutmose IV (KV43), c.1390 BC, are 35 vessels although the sizes are now less exaggerated. Indeed, from this period onwards the heights of glass vessels are comparable to those of stone: for the four complete, 'typical' Egyptian vessels mentioned in Nolte (1969) heights range from 8.1 to 12cm.

How are we to interpret this apparent early interest in producing very large vessels? Clearly, the size of vessels in stone was partly restricted by their function and partly by the precious nature of many of the stones employed. The risks of working large pieces of stone must also be considered, as the chances of encountering flaws or fissures are increased. The oversized glass vessels were probably imports from Mesopotamia, but they demonstrate an intriguing interest in the capabilities of glass to go beyond those of conventional stone. The subsequent levelling of size (to include fewer dramatically large vessels) may be best interpreted as an acceptance of the more 'functional' aspects of cosmetic containers. By the late XVIII and early XIX Dynasties, the sizes of most vessels are indeed in accordance with those of stone. Of 24 complete vessels from various collections and dating to this period 14 are under 10cm in height, with only 4 of the remaining 10 vessels exceeding 12cm (see Table 4.3 for details and sources of data). By this time glass was clearly established as a material in its own right and its size is appropriate to the uses to which the vessels were put (the same, presumably, as those of stone). Its decoration was also well established, and there are no vessels in the earlier vein of decoration which appear to reflect stone in a more 'naturalistic' sense.

Those designing glass vessels probably took their inspiration, if we may use such a word, from the appearance of stones and precious stones / stone vessels in particular, but the material allowed an irresistible degree of exaggeration of the most prized properties of

stone. Eventually the size became more standardised. The decoration, too, was eventually limited to a set variety of styles, but there was never any consistent attempt to recreate the appearance of stone. This apparent highlighting of the difference of glass from other materials suggests that it cannot be seen as an imitation: in many ways, it appears that improvement upon 'natural' sources was implied. That glass eventually settles into a more standardised repertoire of decoration merely implies that it had by this stage been accepted and understood as a material in its own right. There was no attempt to deceive in glass vessel design, but there was an initial period of 'showing off' the unique properties of the material by deliberate contrast to those of stone, which in any case was probably related strongly to glass in broader perceptual categories.

Source	Page Number	Date	Cat. Number	Height (cm)
Matheson 1980	3	1400 - 1200	1	8.5
Matheson 1980	3	1400 - 1200	2	6.8
Matheson 1980	3	1400 - 1200	3	3.3
Von Saldern 1968	19	1400 - 1300	1	9.4
Cooney 1976	141	late 18th Dyn	1731	12.8
Cooney 1976	141	late 18th Dyn	1732	8.7
Cooney 1976	141	late 18th Dyn	1733	10.3
Cooney 1976	142	late 18th Dyn	1734	10
Cooney 1976	142	18th to 19th Dyn	1735	10.6
Cooney 1976	142	19th Dyn	1736	10.3
Cooney 1976	143	18th to 19th Dyn	1737	8.1
Cooney 1976	143	late 18th Dyn	1738	9.1
Cooney 1976	143	18th Dyn	1739	5.4
Cooney 1976	143	late 18th Dyn	1740	15
Cooney 1976	143	18th to 19th Dyn	1741	14.3
Cooney 1976	143	18th to 19th Dyn	1742	8.6
Cooney 1976	143	18th to 19th Dyn	1743	8.8
Cooney 1976	144	late 18th Dyn	1746	15
Riefstahl 1968	20	late 18th Dyn	17	8.7
Riefstahl 1968	20	late 18th Dyn	18	8.6
Harden 1979	1	18th Dyn	16	6
Harden 1979	2	18th Dyn	17	5.8
Caron and Zoïtopoúlou 2008	3	1400 - 1300	1	11.5
Caron and Zoïtopoúlou 2008	3	18th Dyn	2	11.5

Table 4.3 Heights of Twenty-Four Complete Glass Vessels from Various Collections.

Sherratt (2008, 216 - 217) argues that in Mesopotamia, the increasing elaboration of glass objects served as a means to maintain the elite properties of glass. In particular, the application of raised decoration, found in certain glass vessels of this time (far more popular in Mesopotamia than in Egypt), suggests that the skill of the glass worker and the unique properties of glass are being deliberately highlighted. Indeed, although it may appear crude to the modern day observer, the application of raised decoration is in fact rather difficult, considering the necessity of rotating glass while working it (to avoid

sagging and loss of shape): due to the high surface tension of glass, even where a vessel is not marvered, prolonged rotation causes the raised design to sink into the vessel surface[53]. We might compare this with the Egyptian evidence, where the standard repertoire of glass vessels, once established, remains fairly constant throughout the period under consideration. It is apparent that the concerns which led the Mesopotamian industry to increased workmanship in glass did not apply to the Egyptian industry, or at least not to the same extent[54]: in Egypt, the artificial nature of glass was first deliberately highlighted and then accepted as a feature of the material.

A comparable situation in terms of exaggeration and imitation can be found in certain luxury glass of the Roman period, where the production of blanks for glass cameos allowed the glass worker to obtain full control over his material and avoid the difficulties of working stone, the natural inconsistencies of which may not be revealed until part way through the laborious and expensive process of cold carving. Now cameos could be produced to pre-set standards without the need of altering designs to compensate for natural banding (see for example registration numbers BM 1873,0502.167; 168; 178; 190; 192; 199). Vickers (1998, 18) argues that the use of the term 'luxury glass' for the Roman period is misleading, due to the cheapness and ready availability of its raw ingredients: glass, it is suggested, should always be viewed with reference to the more expensive materials it imitates. Whether or not this viewpoint is an exaggeration in itself, the difference between the Roman use of glass and that during the Late Bronze Age is most prominent in the way in which LBA glass design rapidly departed from pure imitation of the stones to which it is compared, whereas the most highly valued glass of the Roman period was always that which most faithfully copied stone in terms of design (and here we are seeing something far more akin to genuine 'deception') and in terms of laborious, time consuming cold working.

Here is Late Bronze Age glass, then, with all the properties which made stone highly prized (its particular colour which was often strong or saturated; its hardness; its consistency; and its shine or lustre) and yet with the potential to be formed into large vessels; to rely not on the natural idiosyncrasies of the banding of stones but to have the pleasing contrasts they possess displayed in the most suitable and prominent places, in any colour and any density of decoration desired. It should hardly surprise us if this aspect of the potential of glass was deliberately highlighted, especially if we consider the production of glass: as a created and / or transformed material, visual reference to its superior properties acted as a means by which the power of its creators was measured.

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[53] Mike Tillerman, replica glass worker (personal communication). See also Lierke et al. (1995, 117).

[54] For further discussion of stylistic development and elite maintenance of stylistic distance in material goods of LBA Mesopotamia see Matthews (2000).

4.d. Case Study: blue glass

> "Amber was viewed as exotic in the Mediterranean because of its magical properties and the mystery surrounding its origins, but it was *beheld* with awe, because its particular optical properties ... had a unique way of arresting the gaze."
>
> Causey (2004, 76)

In order to further explore the previous discussions, a specific 'case study' – that of blue glass – will now be presented. This allows a more detailed comparison between glass and the precious stones it is so frequently associated with, the linguistic terms for glass colour and their re-interpretation, the exploration of symbolic considerations of colour and the idea of colour as a marker of royal control or power.

Blue glass has been selected for this because it is the colour used most abundantly in the production of vessels and small items and because it is also the most frequently encountered in written sources. Opaque and translucent blues of all shades are considered here, as is turquoise.

It is suggested that the linguistic relationship between blue glass and precious stones is more complicated than has previously been assumed, and that symbolism, linguistic colour categories and royal associations are all interwoven in a complex system of reference, which ultimately allows blue glass to be highly valued as a material in its own right, rather than an imitation of more precious substances.

Turquoise and Lapis Lazuli

Turquoise (*mfk3.t*; Akkadian *ashgikû*; Sumerian NA_4AŠ.GÌ.GÌ) is a hydrous aluminium phosphate which occurs in a wide range of colours: the most typical are shades of light blue or blue-green. Unlike the other stones valued in this period, however, turquoise could be vulnerable to heat and light, causing discoloration in the less valuable (less durable) examples, as noted above. It is the blue varieties which are generally brighter, harder and more resistant to wear (Moorey 1994, 101). There are also green varieties which have a wider range of tones so that some are almost yellow, and a whitish variety which is crumbly and unsuitable for working.

Turquoise was certainly among the most highly valued precious stones known and used in Egypt. Romano (2000, 1606) lists it as one of the 'top three' precious stones, the others being lapis lazuli and carnelian (see also Andrews 1994, 102). Turquoise is commonly found at the surface of copper mines and in Egypt came exclusively from Wadi Maghara and Serabit al-Khadim in Sinai (Romano 2000, 1606).

Lapis lazuli (*ḫsbḍ*; Akkadian *uqnū*; Sumerian na4.ZA.gin) is today classified as a semi-precious stone consisting mainly of a blue mineral, haünite (of which lazurite is a variety), a brassy yellow material, pyrite, and a white mineral, calcite, together with relatively small amounts of other minerals (Andrews 1994, 102). Pieces vary from a rich deep blue, speckled with brassy-yellow spots, to a mottled blue and white.

Lapis lazuli was by far the most sought after of the gems known in Mesopotamia and its high status undoubtedly extended to Egypt. Some indication of its high value and limited availability is given in two 13th century B.C. letters (MRS 9 221 RS 17.383 and 223 RS 17.422) addressed to the king of Ugarit from his ambassador at the Hittite court, in which the difficulty of obtaining the stone and its high price are specifically mentioned (Oppenheim 1970, 11 - 12). There are few sources of lapis lazuli in the world: the best known sources today are Afghanistan, Burma, Chile, the United States (Colorado and California) and parts of the former U.S.S.R. (Pamirs and the vicinity of Lake Baikal). Although no written evidence provides unequivocal evidence for the ultimate source of the lapis lazuli used throughout the Near East in the Bronze Age, it is generally agreed that in Western Asia, Egypt and (although here it is rarer) the Aegean, the ultimate source of lapis lazuli was the mountainous region of Badakhstan, northeastern Afghanistan (Moorey 1994, 86 - 91). It was certainly traded to the other areas through Babylonia (as recorded in the Amarna letters and in Hittite correspondence), probably reaching there via the Gulf trade.

Supplies of lapis lazuli seem to have suffered somewhat during the second millennium BC. It was increasingly rare among Mesopotamian seal stones of this period, and was clearly being recycled: it is thought that the disruption of long-distance trade via the Gulf around 1750 B.C. led to a steady decline in fresh supplies of lapis lazuli (Moorey 1994, 90) although it should also be noted that despite the small size and rare occurrence of most lapis lazuli known from the period, occasional finds of large quantities of the stone suggest that much of our data has been skewed by the exceptional value of the stone and its consequent recycling (an example from Egypt is the 19th century B.C. Tod treasure, which contained over 200 items of lapis lazuli comprising pieces of unworked stone as well as seals and ornaments).

There existed a rich terminology for the specific colours and shades of lapis lazuli, more so than for any other precious stone, and the prestige and value of the stone lent it a special role in cult and a wide metaphorical role in literature: it became a standard metaphor for unusual wealth and was synonymous with gleaming splendour, an attribute of gods and heroes (Moorey 1994, 85). Oppenheim (1970, 10) lists the following descriptive terms used for lapis lazuli in Akkadian: 'beet coloured'; 'wine coloured'; 'wild donkey coloured'; a multicoloured variety; iridescent formations compared with the neck

feathers of doves and ravens; 'starry' or 'star like' referring most probably to the golden specks of pyrite found in what we now define as true lapis lazuli; '*Marḫašu*-stone lapis lazuli' (i.e. looking like the stone from *Marḫašu*) is a variant with green dots; and *zagindurū* refers to a greenish lapis lazuli or possibly turquoise. The wealth of descriptive terms for lapis lazuli in the Mesopotamian literature highlights that even within the range of stones accepted as lapis lazuli 'from the mountain' there were scales of value with some variants being more highly prized than others. Significantly, these scales were explicitly related to colour and patterning or colour contrast.

It can be suggested that three factors were at play here in both Mesopotamian and Egyptian perceptions of lapis lazuli, given that it was an import for both areas: firstly, colour (including colour contrast) as a marker of provenance / exoticism and therefore also value; secondly, the symbolic associations of the material, which – given that colour was the primary marker of source / value – extended to its visual appearance; and third, the properties of the material itself which made it desirable, also largely related to colour and visual appearance. We might note at this stage that dark blue glass possessed both the symbolic and aesthetic associations with lapis lazuli, which extended out of colouring (hue and brilliance) and visual properties of the material (not to mention their shared properties of hardness, consistency and durability, discussed above). By contrast, the linguistic evidence explicitly distinguishes between glass and lapis lazuli on the basis of the third criterion: provenance. But how far this extends to the categorisation of glass as an imitative material or lower value substitute is not immediately apparent. This linguistic evidence will now be discussed in more detail, focussing specifically on the use of precious stones as linguistic referents for glass.

'Blue' in the Egyptian Colour Vocabulary

Baines (1985), in response to previous attempts to categorise Egyptian colour vocabulary (see for example Schenkel 1963), attempts to reconcile the evidence for Egyptian colour terminology with the Berlin and Kay paradigm, based on a comparison between colour use (solely focusing on pigments) and Egyptian colour vocabulary from the 3rd millennium B.C. to the Middle Ages (Baines 1985, 282 - 283). A secondary aim of this work was thus the discrimination between Berlin and Kay's (1969) 'basic' and 'secondary' colour terms, discussed in Chapter 3. As noted above, the only 'basic' colour term bearing any relation to blue, under this system of classification, is *w3ḏ*, or 'grue' (green/blue), which Baines (1985, 283) suggests is in any case more strongly focused on green.

One limitation of this approach is noted by Quirke (2001, 188 – 189). *ḫsbḏ* is the term for lapis lazuli, and its use to denote blue is thus seen by Baines (1985, 283) as a secondary colour term (as it is not obviously separated from object category and therefore cannot be considered 'basic'). Quirke, however, uses the example of an XVIII Dynasty series of

incantations designed to protect mother and child as evidence for the use of *ḥsbḏ* as a colour term disassociated with the material lapis lazuli. The surviving text can be translated as follows:

> '[...] a green bead from it (?) of turquoise, and a red bead from it (?) of red jasper...This incantation is to be recited [over] three [beads], one of lapis lazuli, one of red jasper and one of turquoise...'

Although the first part of the text is damaged, the significant point is clear: the colour and material of precious stones, although in some cases sharing descriptive terms, were conceptually separated. Quirke (2001, 189) argues that the first (damaged) part of the text provided a word for blue in the paradigmatic slot for hue of the material lapis lazuli and that the only likely candidate for this is *ḥsbḏ*, here filling the same slot as 'colour terms' although not, under the Berlin and Kay system of categorisation, 'basic'.

This argument is taken further by Warburton (2004), who explores the use of words attached to the term for 'colour' (*iwm*) and possible antonyms. He notes references to the 'colour' of lapis lazuli, turquoise and gold. Like Baines, Warburton argues that the term for 'blue' is not incorporated into the domain of *w3ḏ* (see above) and he considers contexts of use in support of this. For example, while the sky is never referred to as being *w3ḏ*, it *is* referred to as *ḥsbḏ* (lapis lazuli) or *mfk3.t* (turquoise). It is thus suggested that *ḥsbḏ* can be considered a colour term *as well as* a specific term for a material (Warburton 2004, 128). While under the Berlin and Kay model it is accepted that non-basic (i.e. secondary) colour terms were employed, they are always seen as being primarily signifiers of object category rather than acceptable abstract terms. Accepting the abstraction of these terms does not necessarily have to imply limiting their symbolic associations with the minerals from which they derive, of course, but it is clear that such a range of things could be described by them that they cannot be seen as always relating directly to object category.

Similarly, it can be argued that the Akkadian word *uqnu* and the related Ugaritic term *iqni* denote both lapis lazuli and a kind of blue, reminding us again of the similarities between the Egyptian and Mesopotamian treatment of colour in perception, symbol and language. Though in Greece the situation may be somewhat different, forms related to the word *kyanos* (*ku-wa-no* and *ku-wa-no-wo-ko* in Linear B tablets from Pylos and Mycenae) can refer to lapis lazuli or its blue glass substitute (see Nightingale 1998, 213; Sherratt 2008, 212; Bennet 2008, 159 - 160), and there is no additional term or modification (nor do we see the development of such) to make the distinction between glass and these other materials clear.

The 'Two Blues'

Warburton (2004) further argues that, far from having *no* 'basic' term for the colour blue, the Egyptians distinguished two types of blue, a dark, 'lapis lazuli' blue and a lighter blue,

denoted by the term also used for turquoise (*mfk3.t*)[55]. It is thought that the turquoise preferred by the Egyptians was the variety which today might be described as 'blue-green' (Andrews 1994, 102 – 103) and the term may be taken to encompass a similar range of hues as we associate with the colour 'turquoise' today (roughly the same range of hues that are found in the natural mineral). The use of both terms (*mfk3.t* and *ḫsbḏ*) to describe the sky, however, does suggest that the dominant domain for this colour falls within the range of 'blues' rather than 'greens'. Lighter blue glass of the time would thus fall comfortably within the range of *mfk3.t*, whether or not it is deliberately imitating or 'masquerading as' turquoise itself[56].

It is interesting that the 'two blues' distinguished by the Egyptians were also the two most popular colours for glass. One may be tempted to link this directly to the imitation of lapis lazuli and turquoise, and at first glance the textual evidence appears to support this. Closer inspection, however, reveals a far more complex and interesting situation.

Associations of Blue in Egyptian Symbolism

The links between certain colours and the materials they are associated with – symbolically or otherwise – alert us to the fact that colour in itself conferred certain properties and in the case of amulets or funerary equipment, protection. Blue was the colour of divine truth and justice and as such was regarded as particularly important. It was worn on the breastplates of priests, and the blue or 'war' crown which came into vogue during the New Kingdom reflected an ascendance of the popularity of blue as the colour of the Gods, a colour which could thus offer protection (Ragai 1986, 76 – 77). It can also be argued that the colour of lapis lazuli as well as the material itself was endowed with magical properties. An early first millennium magic text from Assur (KAR 238 r.17) demands a string of blue wool, the colour of which is described as 'SÍG.ZA.GÌN.KUR.RA' ('moutain-lapis-lazuli-coloured-wool') and other examples of the magical efficacy of this colour of wool are known (Oppenheim 1970, 12).

As noted above, minerals were the primary reference points for colours in many contexts, so it is hardly surprising, given the importance of turquoise and lapis lazuli as minerals, that these two should be intrinsically associated with the understanding of blue. Further,

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[55] The use of more than one term to describe blue has also been commented upon previously, including by Baines (1985, 287), but the mineral associations of the terms for lazuli and turquoise had led to their classification as 'secondary' terms relating primarily to the objects they also denote.

[56] Again there appear to be parallels between the colour categorisation in Egypt and neighbouring areas. Two blues, also, can be tentatively ascribed in the early Greek language (stemming from the LBA): the lighter blue, *glaukos*, could also refer to shimmering or glittering properties while the darker hue appears to be described by the much-debated *kyanos*, which also has a range of meanings (see Deacy and Villing 2004 for a more detailed discussion of these terms). Warburton (2004, 128) also notes a possible distinction between darker and lighter blue in Akkadian.

the strong separation of blue into two linguistic and probably perceptual categories may have been directly associated with the ties between minerals and colour designations. Given the strength of these ties, it would be wrong to assume that only in the case of glass was the reference to precious stones of importance. I suggest that this reference to precious stones in describing glass was a reference not to the material of glass but to its colour, the two of which were to some extent rendered inseparable by language and religious belief; the very word for colour also meaning the character or essence of a thing (on the roots of the term for colour, see Baines 1985, 284). The symbolic associations held by colours factor in all selection, including that of pigments and dyes.

The associations and symbolic potency of the dark blue shade referred to as *ḥsbḏ* coupled with the linguistic considerations noted above illustrate that the shade of blue itself became significant and indeed had been so for a long time before it was reproduced in glass. This may have initially been associated with its reference to lapis lazuli, but it is now clear that it does not necessarily signify that material immediately, rather it belongs to a web of reference related to colour, magical potency, and source, demonstrating the interconnectedness of Egyptian (and indeed, Mesopotamian) thought and symbolic references.

Cobalt, access to raw materials and royal control

Chemical analyses conducted to date have revealed that copper was the most abundant colorant used in the production of LBA glass. Cobalt was also used as a glass colorant in Egypt and cobalt-coloured glass was imported into the Aegean, probably from Egypt[57]. Almost all cobalt-coloured glass known from Egypt appears to have been coloured using treated cobalt alums from two of the oases (Dakhla and Kharga) in the Western Desert (see Chapter 3).

Royal expeditions, according to remaining records, were either trips to desert mines or quarries, or journeys to barter for goods with other peoples. Egyptian sources treat all expeditions as similar activities and report them with standardised vocabulary (see Bleiberg 2000, 1377 – 1379). The records suggest that expeditions of both sorts were specific activities, directly instigated by the king, often in order to obtain a specific material for a specific purpose: an example from the New Kingdom is an inscription recording Hatshepsut's expedition to Punt to obtain incense for the Temple of Amun. The

[57] Mesopotamian production of cobalt-coloured glass also seems to have occurred, though it was not as widespread as in Egypt. A dark blue fragment of glass from Kassite Nippur was found to be coloured with cobalt, and the absence of nickel or zinc in this piece suggests that the cobalt was not from the Egyptian source, and may have been Iranian. Compositionally similar fragments are also known from Eridu from as early as the Ur III period (Moorey 1994, 208 - 210).

first major exploitation of cobalt from the Dakhla and Kharga Oases within Egypt appears to have occurred during the reign of Tuthmosis IV (1400 - 1390 BC), coinciding with the earliest period of probable glass production within Egypt and likely to have been directly linked to this. The pigment 'Amarna Blue' (a mixture of $Co(M)Al_2O_4$ and $CaSO_4$) was developed at this time and was used in addition to Egyptian Blue ($CaO.CuO.4SiO_2$) (Uda et al. 2002). It is only known from the XVIII and XIX Dynasties and it was mainly used to colour pottery, such as that found at Malkata and Amarna (Shortland et al. 2006a). As noted by Keller (1983), cobalt pigment was *not* associated with the non-royal site of Lisht. Interestingly, Amarna Blue is light in colour and would not therefore have had direct visual links to the use of cobalt as a glass colorant. Rather, it may illustrate the importance of royal control over resources and the acquisition of cobalt in particular, manifested through the use of particular pigments and specific colours which could not be reproduced using other ingredients.

The New Kingdom marked a particularly strong period of centralised rule in Egypt, facilitating the restriction of exchange and the mechanisms through which goods could be obtained. Kemp (1989) argues that a lower level of exchange is nonetheless likely to have arisen within Egypt in order to satisfy individual demand: certain records from the workers' village at Deir el-Medina may support this (see Kemp 1989, 232 – 248; Lesko 1994). Perhaps more relevant to a high status material such as glass are changes in private tombs noted from the time of Tuthmosis III, which may reflect an increase in status of non-royal elites. For the first time images of kings became common in private tomb chapels of high officials, as were those of foreigners bearing tribute (Robins 1997, 138). This rise in the 'middle class' and emulation of the high (royal) elite may be reflected in the increased production of small faience trinkets, such as the large number known from Amarna (see Shortland 2001). The limited distribution of glass suggests that the technical skill of its production, discussed above, served to reinforce the status of the material. This may not be a geographical signifier as with lapis lazuli, but it had the same effect in limiting its availability, an effect augmented by the measures taken in order to obtain certain colorants; notably cobalt but probably also antimony and lead, required for the production of yellow, white and light blue or turquoise opaques. In a period where the status of non-royal elites was increasing, glass – far from providing a lower value imitation of a high status material – served as a means to visibly reinforce royal status through its limited distribution, complexity of production technology, symbolic colour associations, and the efforts to obtain certain ingredients (colorants) which required royal intervention.

Glass is Created Colour: blue glass

An additional point might be made with reference to the significance of blue glass. It is interesting to note that, of all the terms which could be used to denote glass makers and

workers (the terms in this case deriving from the material, as discussed above), it appears that there is only one, and it is applied universally (that is, regardless of the colour to be produced): this term is *ḫsbḏ*. In these contexts it appears along with associated modifiers, describing the particular rank of the craftspeople involved, during the New Kingdom, at the time that glass production first entered Egypt (Shortland 2007, 264). Thus it is highly likely to refer solely to this craft and not to lapis lazuli working.

The importation of lapis lazuli has often been seen as the motivation behind production of dark blue glass. This may well have served as part of the impetus behind the initial production of glass in Mesopotamia, and the ability to ensure a steady supply of a similar material with the same valuable colour must have been a key benefit to its production. But the clear distinction between the two materials suggests that there was more than a motive of substitution behind glass production. The ability to create a dark blue, hard, brilliant material with unique properties (it can be melted) may have been more important than its explicit relationship to lapis lazuli. Dark blue *in general* had special connotations which were inextricably related to the symbolic associations of lapis lazuli, minerals often acting as the primary referents for colour itself. The importance of creation rather than substitution becomes more apparent when we compare the production of dark blue glass with that of turquoise or light blue. As noted, the Egyptians had access to turquoise (and that other prized stone, carnelian) in their own territories: turquoise could be obtained from Sinai, and the possession of it was thus not reliant upon long distance exchange with Babylonia. Yet it is clear that a variety of shades of lighter blue glass were deliberately produced and that these were also used as base colours for vessels and small items. As noted previously, it appears that the ability to produce glass in as wide a range of colours as possible was of major importance, despite the fact that certain of these colours held more potent symbolic associations than others. The production of glass was in itself a symbol of royal control and cannot be held to be only a substitute for gaps in the acquisition of other materials.

Thus blue was so symbolically important that glass could be valued on its shade of blue. Certainly this was not the sole factor in determining the value of glass, but it did provide a very important conceptual niche for glass. Linguistic studies tell us that descriptions of colour were often embedded in reference to particular objects, but that this does not mean they always refer primarily to these objects (see Warburton 2004, 126): lapis lazuli *was* blue, a specific type of blue, and this type of blue was directly and materially related to its 'symbolic' associations such as the night sky (see Andrews 1994, 102), and therefore also to glass. The fact that glass was blue and brilliant and uniform throughout distinguishes it from blues applied as pigments and even faience. The idea that colour was an intrinsic feature of a material or object (both in terms of identification and essence) meant that the production of a specific colour of glass was an act of creation. So in a sense, as was lapis lazuli, cobalt- or copper-coloured glass *was* blue.

5. Electron Probe Microanalysis (EPMA)

5.a. Background

The key practices and principles of EPMA and other electron microscopic techniques such as Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM) have been amply discussed in the existing literature (see for example Pollard et al. 2007, 109 – 11; Goodhew et al. 2001; Newton and Davison 1996; Reed 1993; Barber and Freestone 1990; Meeks 1988; Olsen 1988; Bimson and Freestone 1983) and there are a number of published references to the use of EPMA in particular in characterising ancient glass (see Nikita and Henderson 2006; Henderson 2000; Henderson 1988a; Green and Hart 1987). Thus a relatively broad background to EPMA is provided below, and the reader is referred to a number of published sources on specific points of interest. The methods undertaken are specific to the equipment available at the University of Nottingham and are therefore provided in a separate section. Image analysis was also applied to the images obtained with EPMA, and a third section is thus provided to give a broad background to the technique.

EPMA has a number of features which make it suited to the demands of this study. Because it uses a higher beam current than a typical SEM, thus exciting the emission of an increased number of characteristic X-rays from the sample, the electron microprobe is capable of higher detection limits and accuracy than SEM, and provides quantitative chemical information on most elements. The microprobe used here is also equipped with detectors for secondary and backscattered electrons, allowing both compositional and topographic imaging. For quantitative compositional analysis, WDX (see below) was used rather than EDX as it provides a higher resolution for quantitative analysis due to the use of specific crystals for the detection of different elements.

The Principles of EPMA

EPMA involves the generation of a micro-beam of electrons using an electron gun. These are focused onto the mounted sample using an electrostatic lenses (Henderson 2000, 17), causing a number of energy emissions (see below), of which characteristic X-rays, backscattered electrons (BSE) and secondary electrons (SE) are detected. The main components of the electron microprobe are illustrated in Figure 5.1.

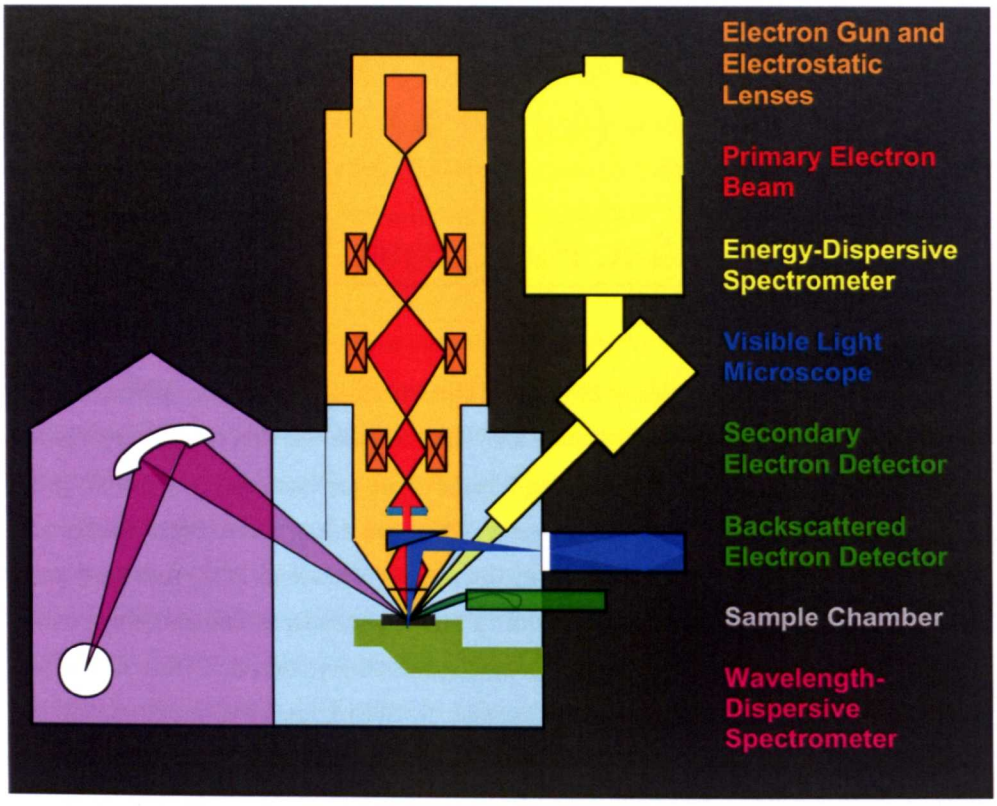

Figure 5.1 Electron Microprobe Components.
After University of Minnesota Electron Microprobe Laboratory, online resource (probelab.geo.umn.edu).

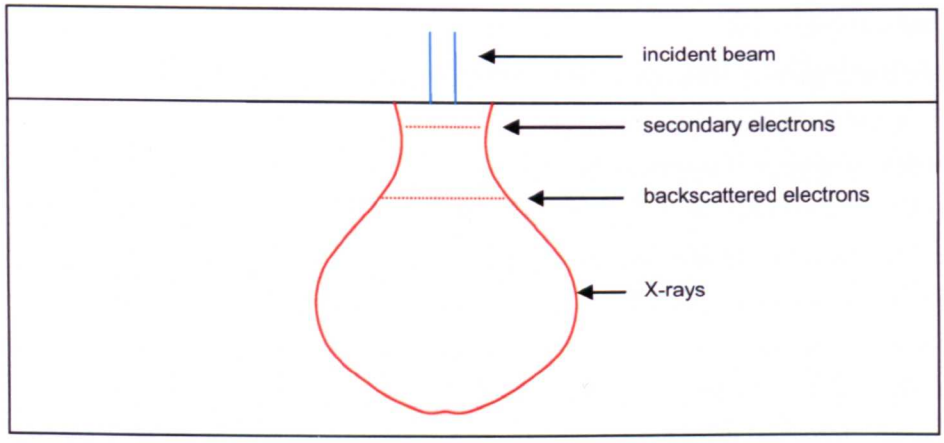

Figure 5.2 Interaction Volume for Signal Generation in EPMA.
Schematic two-dimensional representation of the relative regions of the interaction volume –up to several microns in diameter – from which the energy emissions relevant to the present study originate.

Electrons are fired from a tungsten-filament thermionic electron gun, accelerated to energy between 1keV and 30keV and demagnified by the condenser lenses until the beam hits the sample, with a diameter which can be as small as 2 – 10nm. The region into which the electrons penetrate the sample is known as the interaction volume (see Goodhew et al. 2001, 126). It is within this region that the various energy emissions are generated as a result of inelastic scattering, the amount and type of emission varying with depth as the

primary electrons penetrate further and lose energy. Energy emissions generated within this area do not all escape the sample surface, but those which do can be measured appropriately. Figure 5.2 shows the characteristic 'tear drop' shape and depth of the interaction volume from which emissions escape the sample surface and are measured.

Characteristic X-rays and Quantification

X-rays are a form of electromagnetic radiation with wavelengths between 10^{-8} and 10^{-12}m. They are produced by interactions between external electrons and the electrons in a given energy shell of an atom. As they are part of the electromagnetic spectrum, X-rays can be viewed as being made of photons, discrete quanta of energy. For electromagnetic waves of frequency v the energy (E) of each photon is:

$$E = hv \quad [1]$$

where h is Plank's constant (h=6.6256 x 10-34 Js^{-1})

When electrons or X-rays of sufficient energy are fired at a sample of material the electrons in the innermost energy levels (or 'shells') of the atoms in the material are ejected. This leaves a vacancy in the shell that was once occupied by the ejected electron and which can now be filled by an electron from a higher energy level. This electron must lose some of its energy in order to fill the lower energy level, as shown in Figure 5.3. The quantity of emitted energy is equal to the difference in the electron energy levels:

$$hv = E_K - E_L \quad [2]$$

where hv is the energy taken to move from one electron state to another

When the energy levels involved are in the K and L or L and M shells (shown) the photons of electromagnetic radiation absorbed or emitted will be within the range defined as X – rays (see Jones 1992, 5).

Because atoms and molecules can only emit or absorb electromagnetic radiation in fixed quanta corresponding to the differences between energy levels (determined by atomic number) the energy that is emitted and measured is said to be *characteristic* of the particular type of atom from which it was emitted.

Transitions between inner-shell electrons are important to micro-chemical analysis since the innermost energy levels are those least affected by the chemical environment of an atom, and are therefore most characteristic of the atom. By measuring the wavelengths (and thus the energy) of X-rays emitted from the inner shells of atoms in a material using an energy dispersive X-ray (EDX) or wavelength dispersive X-ray (WDX)detector, the composition of the material can be determined.

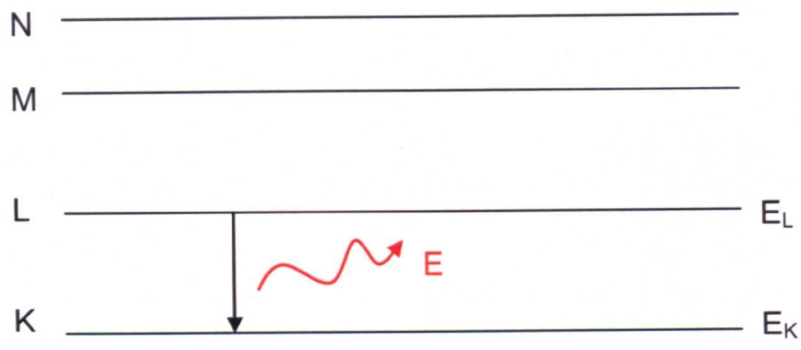

Figure 5.3 X-ray Emission.
An electron from the L shell fills the vacancy in the K shell and the excess energy (E) is removed in the form of an X-ray photon.
After Pollard and Heron 1996.

The detection of characteristic X-rays is expressed by Moseley's Law, which relates the atomic number Z to the observed wavelengths (λ) of the X-rays:

$$v = \frac{c}{\lambda} = a\,(Z^2 - \sigma^2)\left[\frac{1}{n_2^{\,2}} - \frac{1}{n_1^{\,2}}\right] \quad [3]$$

where n is the energy level number
a and σ are constants

This information is obtained in a series of peaks, or emission lines, the maximum wavelength of the series being related to atomic number. It should also be noted that there are a number of sub-shells within each energy level K, L, M, etc. and this results in a number of emission energies, denoted K_α, K_β, and so on. The measured emission energies provide the basis for qualitative analyses to be conducted.

By measuring the intensity of the peaks it is also possible to conduct quantitative analyses. The number of characteristic X-ray counts from the sample within a fixed interval of time is compared with the number arriving from a standard of known composition within the same interval. Using 'spec' to refer to the sample (specimen) and 'std' to the standard, the concentration of this element in the sample is thus given by:

$$C_{spec} = N_{spec}/N_{std} \times C_{std} = k \times C_{std} \quad [4]$$

where C_{std} is the known concentration in the standard
N is peak count minus background count

As the sample counts and standard counts are not taken at the same time, it must be ensured that the same conditions of analysis are maintained for both. It is also important to ensure that the composition of the standard is as close as possible to that of the specimen.

Matrix effects must also be taken into account: X-rays from lighter elements are more readily absorbed by a matrix of higher atomic weight before leaving the sample. Assuming the analysis of a flat, polished sample, the complications arising from the ratio of sample to standard counts, *k*, is used to calculate approximate values of corrections to a number of effects. These are: atomic number (Z), concerned with the efficiency with which an element generates X-rays; absorption (A) concerned with distance travelled by X-rays before emission from the sample; and fluorescence (F) concerned with the excitation of lower energy fluorescent radiation by high energy X-rays and particularly affecting elements of similar atomic numbers in close proximity within the sample. The computer correction of these errors is known as the ZAF technique and for solid samples analysed with WDX enables concentrations to be measured with a deviation of 2% of the total concentration, though for minor and trace elements the deviation can be higher (Goodhew et al. 2001, 201).

Back-scattered and Secondary Electrons

Backscattered electrons (BSE) are incident electrons which are not absorbed into the sample after impact: they are 'scattered back' and can thus be detected. The fraction of incident electrons that are backscattered is highly dependant on atomic number, increasing from 10% for C to over 50% for U, as illustrated in Figure 5.4.

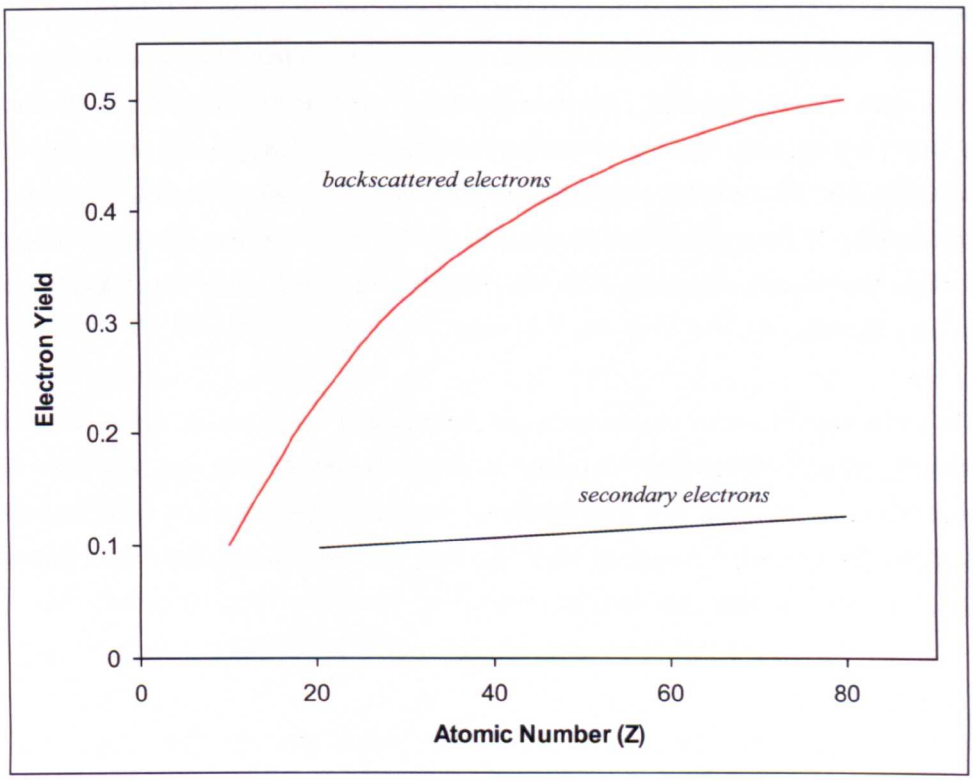

Figure 5.4 Electron Yield as Function of Atomic Number.
Higher atomic numbers have a higher backscattering coefficient. Note that the secondary electron yield is also affected by atomic number, though to a much smaller extent.
After Reed 1993, 55.

The result of this is that backscattered electrons can be used to build up an image showing variation in average atomic number across the sample (Meeks 1988, 23). Backscattered signals are affected by surface topography, as the angle of the surface affects the fraction of the electrons backscattered, and the detector 'sees' the specimen from one direction only, causing shadowing effects (Reed 1993, 55). For flat polished samples where topography is not an issue, however, compositional contrast within the sample is almost entirely determined by atomic number, excepting holes which will often appear as dark patches in BSE images.

Although secondary electron (SE) imaging is less relevant here – as polished samples were used – it merits a brief discussion as it has been used in order to determine whether darker areas visible on some samples are the result of holes (produced, for example, by the plucking out of inclusions during polishing) or areas with lower atomic number. It was also used as the primary method of obtaining images when working with the SEM (for the 14 samples selected for potential ToF-SIMS analysis) as the equipment used has far better resolution in SE mode, and it is capable of producing images which show variation in composition when topography is not a strong factor.

Secondary electrons originate from inelastic collisions between the high energy primary electron beam electrons and electrons in the specimen. The term is used to describe those electrons which escape from the sample surface with energies below about 50eV. Although a few may be primary electrons at the very end of their trajectory (Goodhew et al. 2001, 34) most are electrons to which a small amount of energy has been transferred within a short distance of the sample surface: the lower energy of the secondary electrons means that only those generated from within a few nm of the sample surface will escape the sample. The yield of secondary electrons is high, usually with one or more emitted per primary electron.

The abundance of secondary electrons and their surface origin makes them ideal for imaging, particularly topographic imaging of the sample surface. They can also provide broad compositional data as the SE coefficient is sensitive to the surface condition and electronic structure of the material, though it does not vary monotonically with atomic number as does the backscattered coefficient.

Sample Preparation

Samples between 2 and 5mm were taken using a tungsten glass sampler and fine tweezers. Where beads were sampled, glass was taken from the inside edge of the bead's thread hole unless a more suitable area (such as an area of previous breakage) was noticed. They were double labelled and stored in glass vials until mounting.

The samples were arranged in plastic moulds (5 – 15 samples per mould) lined with a Buehler Release Agent. Buehler epoxy resin was then mixed, poured into the mould, and allowed to dry for 16 hours at room temperature. The resin blocks containing the samples were then ground and polished to expose the surface of the samples and remove scratches and fine lines which might interfere with analysis. A Buehler Beta Grinder-Polisher, typically set to between 150 and 200 rotations per minute, was used for both the grinding and polishing stages. For grinding, Buehler SiC 10" grinding paper (grits P800, P1200 and P2500) was used under running water. Coarser paper was avoided due to the delicate nature of the samples. Samples were cleaned with detergent and dried with paper towels in between stages. For the polishing phases, Buehler PSA 10" Texmel (one each for 6 μm and 3μm) and Microcloth (one each for 1μm, 0.25μm and final polishing) were affixed to the grinder-polisher. Samples were polished using 6μm, 3μm, 1μm and 0.25μm grades with the addition of Buehler Metadi Supreme Polycrystalline Diamond Suspension in spray form. For the final polishing stage the wheel was set to 60 rotations per minute and a non-crystallising colloidal silica polishing suspension was applied. In between each polishing stage the sample blocks were washed with detergent, thoroughly rinsed, sprayed with ethanol and dried with a burst of hot air. The washing process was repeated several times after the final polishing stage to ensure that no colloidal silica remained on the sample surface.

In order to remove all traces of each previous stage of grinding or polishing, the samples were ground / polished in a single direction and rotated by 90° in between each stage so that any scratches from the previous stage could be identified if they remained on the surface. During the grinding process this could be achieved by eye but for the polishing stages the sample surface was examined using an optical reflected light microscope.

Each sample block was photographed under a reflected light microscope and the location of various samples (noted in the initial mounting into sample blocks) labelled. The samples were then cleaned in a sonic bath (isopropanol) and coated with a thin layer of carbon to avoid charging, using an Emitech K550X carbon coater.

Instrument and Analysis Conditions

The instrument used for this study was a JEOL JXA-8200 electron microprobe with combined wavelength and energy dispersive microanalysis. The instrument has four spectrometers which use varying crystals, depending on the element and concentration measured. The crystals used for the detection of each of the 26 elements analysed (measured and listed as oxides in the results) are listed in Table 5.1. 'H' type crystals (LIFH and PETH) are capable of the measurement of smaller concentrations, and were selected for the detection of Zn, Sn, Ni, Co, Mn, Cr, Zr and Sr.

Element	Electron Shell	Crystal
Na	Ka	TAP
Cu	Ka	LIF
K	Ka	PETJ
Zn	Ka	LIFH
Si	Ka	TAP
Ag	La	PETJ
Ti	Ka	PETJ
Sn	La	PETH
Al	Ka	TAP
Fe	Ka	LIF
Ba	La	PETJ
Ni	Ka	LIFH
As	La	TAP
Cl	Ka	PETJ
Ca	Ka	PETJ
Co	Ka	LIFH
Mg	Ka	TAP
Pb	Ka	PETJ
Sb	La	PETJ
Mn	Ka	LIFH
V	Ka	LIF
S	Ka	PETJ
Cr	Ka	LIFH
P	Ka	PETJ
Zr	La	PETH
Sr	La	PETH

Table 5.1 Crystals used in the Detection of Different Elements with WDX
Data for the EPMA results presented in Appendix 2. 'H' type crystals (LIFH and PETH) are capable of measuring smaller concentrations.

A Corning B glass standard was analysed along with the samples for each run of analysis. Table 5.2 presents the published composition for the Corning B standard, compared with the measured composition from a representative run of the microprobe in the present

study. It should be noted that the use of standards is not always 100% accurate: they may vary slightly from the published composition, and internal heterogeneity has been found to occur, the possibility of which is particularly relevant where minor and trace elements are concerned[58]. Nonetheless, the results presented were accurate to within 1.7% deviation for the total composition. The comparison reveals some problem with the detection of SnO, which may thus have been under-represented in the results of EPMA.

Oxide	Results	Quoted
Na_2O	17.97	17.26
CuO	2.72	2.7
K_2O	1.061	1.1
ZnO	0.202	0.2
SiO_2	59.24	61.55
TiO_2	0.094	0.1
SnO_2	0	0.04
Al_2O_3	4.49	4.22
FeO	0.298	0.35
BaO	0.014	0.14
NiO	0.091	0.09
As_2O_5	0	0
Cl	0.175	0.2
CaO	8.67	8.71
CoO	0.047	0.035
MgO	1.093	1.19
PbO	0.428	0.4
Sb_2O_5	0.543	0.46
MnO	0.242	0.28
V_2O_5	0.086	0.03
SO_3	0.502	0.54
Cr_2O_3	0.009	0.005
P_2O_5	0.762	0.84
ZrO_2	0.018	0.025
SrO	0	0.01
Total	**98.77**	**100.5**

Table 5.2 Published Composition of Corning B Standard Compared with EPMA Results.

Given as percentage oxides. The results were recorded on 04.12.08 during analysis of samples from the Beck Collection and are compared to the quoted composition of the Corning B standard. Results are representative of the entire sample set.

[58] Information provided by Edward Faber, Dept. Archaeology, University of Nottingham; personal communication.

The electron beam was defocused to 50μm in order to prevent the volatisation of low atomic number (Z) components, in particular Na and K. Two to three spot analyses (using WDX) were taken for each sample, or for each phase where the sample was heterogeneous, and these were combined in the final results presented. Single spot analyses were also undertaken for inclusions although it should be noted that due to the defocused beam size these results include data from the adjacent glass matrix. As discussed in Chapter 6 the WDX spot analyses of opaque inclusions can also include the glass matrix beneath the inclusion, depending on the size of the crystal and how much of it remains after polishing. For the purposes of identifying the dominant components of the inclusions, however, this approach was deemed sufficient: a more detailed analysis of the chemical make-up of opacifying inclusions is provided in the ToF-SIMS work presented in Chapter 6.

Statistical Data Manipulation

Multivariate analysis of the quantified EPMA results was conducted in the form of principal components analysis (PCA) using the programme MV-Nutshell, specifically developed for archaeological applications by Richard Wright (© 1993-94).

The goal of PCA is to extract from the data (in this case, the tables of percentage quantity of various oxides for a number of samples) those factors, or 'principal components', which capture the largest amount of variance. This involves the linear transformation of correlated variables into pairwise uncorrelated variables (Baxter 1995, 513): in this case scores based on the first four transformed variables were plotted to investigate or display structure in the data. PCA is primarily an exploratory tool, which is how it is used here: any suggestions highlighted by PCA were subsequently investigated in terms of the raw data.

PCA was conducted on the results of the chemical analyses, and the PCA results were plotted against one another (for example, PC1 v PC2; PC1 v PC3). The component plots were reproduced several times, after outliers or compositionally distinct groups were identified and separated, and the data was successively resubmitted in order to establish the archaeologically significant variables within each group.

Archaeometric data is often normalised to bring the total oxide content of each sample up to 100%. However, this can hide systematic and other errors, and has not been done here. Moreover, this is not a prerequisite of the statistical analyses undertaken here and such a procedure was not performed unless thought to be specifically appropriate for questions in relation to selected data. Values for elements which were either below the level of detection of the microprobe or were not present, however, were changed to 0 in order for the software to operate effectively.

Comparability of Results

A number of published results are discussed in both Chapter 3 and the results section of the present chapter. It is thus worth making a comment about the comparability of results obtained from different programmes of analysis as the accuracy and precision of these may vary. In general, two programmes of analysis which use the same technique (in this instance, EPMA) will be more directly comparable, at least in terms of accuracy. Conclusions based on major – and to some extent, minor – elemental composition will also generally be broadly comparable between not only instruments but also different techniques which are capable of detecting the relevant elements. In the context of the present study, correlations between elements are taken as more directly comparable to the conclusions of other programmes of analysis, as they relate primarily to correlations found in raw ingredient sources. Absolute amounts, however, are more reliant upon the precision of the technique and instrument being used and are thus not used to distinguish between my own results and those of published studies at concentrations of less than 1 – 2%.

In any case, such comparisons are not always possible. In the results section of the present chapter, the results of a published programme of trace element analysis (Walton et al. 2009) are discussed with reference to the question of recycling. Because they were obtained using an ICP-MS based technique, however, these were not directly comparable to the results obtained in the present study and were accordingly treated and discussed as a separate data set.

5.c. Image Analysis Background and Method

While high profile techniques such as ToF-SIMS are providing new data on the development of crystalline inclusions within a glass matrix, as explored in Chapter 6, it is also important to consider techniques through which a larger sample selection may be analysed in order to obtain information about production technology and ingredients of opacified glass. Image analysis has been used in combination with EPMA data in the present study in order to examine images of samples containing opacifying inclusions.

The programme Image J was employed in order to convert BSE images from EPMA into binary images, and to gain information about the number and size of inclusions in each of these. Image J is a publicly accessible programme developed by Wayne Rasband, National Institute of Health, USA.

BSE images (see above) were taken for every sample. Of these, any which showed evidence of heterogeneity (due to opacifying inclusions, for example) was imaged in more detail. A minimum of two BSE images were taken for such samples, at magnifications of x500 and x1000, in order to maintain consistency within the sample group. Higher magnification images showing individual inclusions of particular size or shape were also taken, but for the purposes of image analysis it was those areas which were most 'typical' of the overall sample which were selected. The BSE images taken for each sample can be found in Appendix 4. The numerical data generated with Image J are given in Appendix 2.

A binary image distinguishes features in an image (these are defined as a contiguous group of pixels, corresponding to structures or objects in the image; in this case, to inclusions in the homogeneous glass matrix). This requires that the greyscale images produced by analysis of back-scattered electrons in samples of ancient glass are transformed into black and white images, clearly delineating between the inclusions and the matrix. The can be achieved through adjusting the image threshold: the brightness for each pixel is compared to a threshold value and pixels that are darker are set to black while brighter ones are set to white.

Because the original BSE images are rendered in greyscale rather than colour this was a relatively straightforward task, but it did require some measure of interpretation. Although brightness and contrast were generally set at similar levels for the images taken on the electron microprobe, it is nonetheless unavoidable that there are some differences[59]. In particular, the presence of very bright patches on the image such as lead-antimonate

[59] For a more complete discussion of the advantages and drawbacks of a human element in setting a threshold see Russ and Russ (2008).

inclusions (bright because of the high atomic number of lead), will affect the contrast of the entire image. It was thus necessary to separately alter the threshold for each sample image, as shown in Figure 5.5. In general, it was attempted to alter the threshold so that all inclusions visible in the image were rendered white and therefore included in the analysis. In some cases, however, particularly where only very small inclusions were present on the image and the contrast was thus less affected by the presence of large, bright crystals, it was necessary to set a threshold which excluded some inclusions from the analysis, as these were so faintly represented as to suggest they were far below the sample surface.

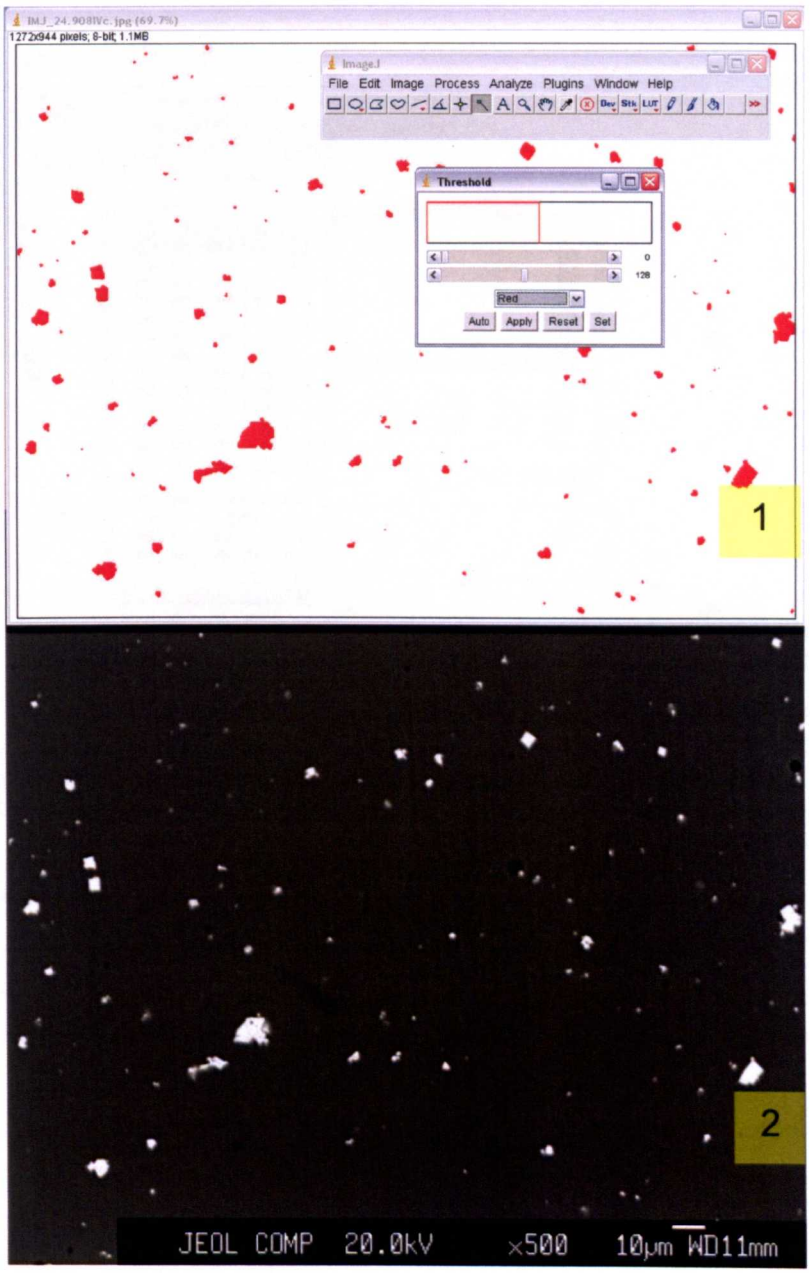

Figure 5.5 Setting the Threshold in Image J.

[1] Setting the threshold for analysis in Image J for x500 magnification image of opacifying inclusions in sample MAA 1924.908IVc.

[2] Original sample image, with some less distinct bright patches perhaps corresponding to inclusions deeper in the sample.

Image J allows the calculation of the number of inclusions present, their size and distribution, as shown in Figure 5.6. These data were collected for each image, at both magnifications (x500 and x1000). They were then entered into Microsoft excel charts allowing comparison between samples. For the purposes of the present study, the key factors for analysis were the size and quantity of opacifying inclusions. The shape of inclusions is also of importance as it helps to define the process of crystallisation explored in more detail in Chapter 6. The small size of most inclusions, however, precludes the full identification of their crystal morphology using EPMA. Where possible the shape of inclusions was thus noted by eye.

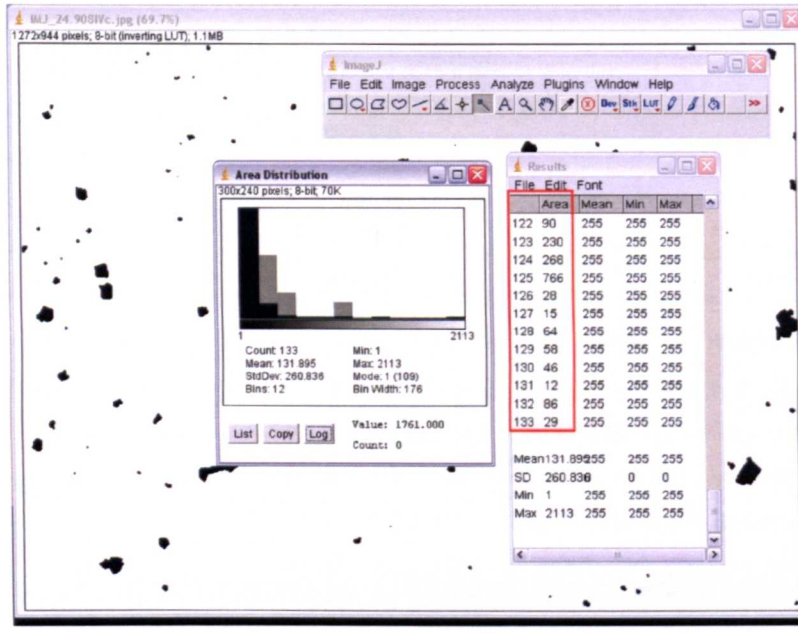

Figure 5.6 Calculation of Inclusion Quantity and Size in Image J.
Calculation of number of inclusions and their size using Image J, for x500 magnification image of opacifying inclusions in sample MAA 1924.908IVc. Each inclusion is numbered and its relative size (in pixels) noted, as highlighted in the red boxed area.

Because two of the processes described – selecting an area for analysis, and setting the image threshold – involve a measure of interpretation of the part of the analyst, it was necessary to check the consistency of the data produced. As noted, for several samples more than one image was taken at each magnification in a number of locations. The relevant results include the total number of inclusions and the number of pixels covered by each inclusion. The total summed pixel counts for all inclusions present (i.e. the total number of pixels within the area of the image which were taken up by inclusions) was divided by 1000 for convenience, and this was multiplied by the total number of inclusions. The result allows comparison between samples, and between images of the same sample taken at different magnifications. It was found that the data generated from different areas and different magnifications within the same sample were roughly consistent, and were distinct from other samples. For example, this exercise generated

three results for sample 24.908I (white opaque) between 24000 and 48000; four results for 24.908III (green translucent), between 36 and 63; and four results for 24.908IV (yellow opaque), between 1300 and 2400.

Where relevant the size of inclusions could also be compared so that, for example, samples with a number of very small inclusions and one or two larger inclusions could be distinguished on this basis.

5.d. Results and Discussion

The results of EPMA are presented below. The results are broadly divided into two main groups: regional and chronological distinctions are dealt with first, followed by issues surrounding production stages and coloration. As well as LBA samples from Egypt, Tell Bazi and Deir 'Ain 'Abata, samples from the early to mid 1st millennium B.C. were taken from Egypt, Mesopotamia, Italy and Greece. The sampling strategy has been outlined in Chapter 2, and full details of all objects sampled can be found in Appendix 1.

Regional and Chronological Distinctions

Figure 5.7 shows the first set of results obtained with PCA, after the removal of samples with a low total percentage on analysis[60], plotted by the first two principal components (PC1 plotted against PC2). Figure 5.8 shows the third iteration of results, following the removal of a number of outliers: the majority of samples removed were non-Egyptian in origin (including those from Ur, discussed below), and it is apparent that almost all Egyptian samples – regardless of date – occupy a separate region of the chart to those from Europe (Italy and Greece). The few Mesopotamian samples which were not removed after the first and second PCA runs are grouped within the area occupied by Egyptian samples. The principal oxides responsible for the variation can also be seen on this chart.

Although initially illustrated with PCA, these findings better examined through a more detailed consideration of the concentrations and ratios of various oxides measured, as approached below with reference to some well-established categories[61] for distinguishing between the raw ingredients and geographical sources of various known glasses. PCA indicates that variation is most strongly affected by a number of apparent groupings of elements and oxides: MgO, K_2O and P_2O_5; PbO and Sb_2O_5, the latter associated with CuO and As_2O_5; CoO and Al_2O_3; and a group which comprises a loose association between MnO, Ag_2O, NiO, Cl and TiO_2. Where they were found to reflect archaeologically interesting distinctions in the data these categories are explored in further detail below.

[60] Samples with a total percentage deviating from 100% by over 3%. This can be caused by significant difference between the standards used in EPMA and the composition of the samples analysed, so that samples which are heavily weathered, for example, or samples of highly unusual composition (for which the equipment has not been calibrated) will tend to produce a lower percentage.

[61] For a more detailed background to these categories and well-recognised broad distinctions between glass, see Chapter 3.

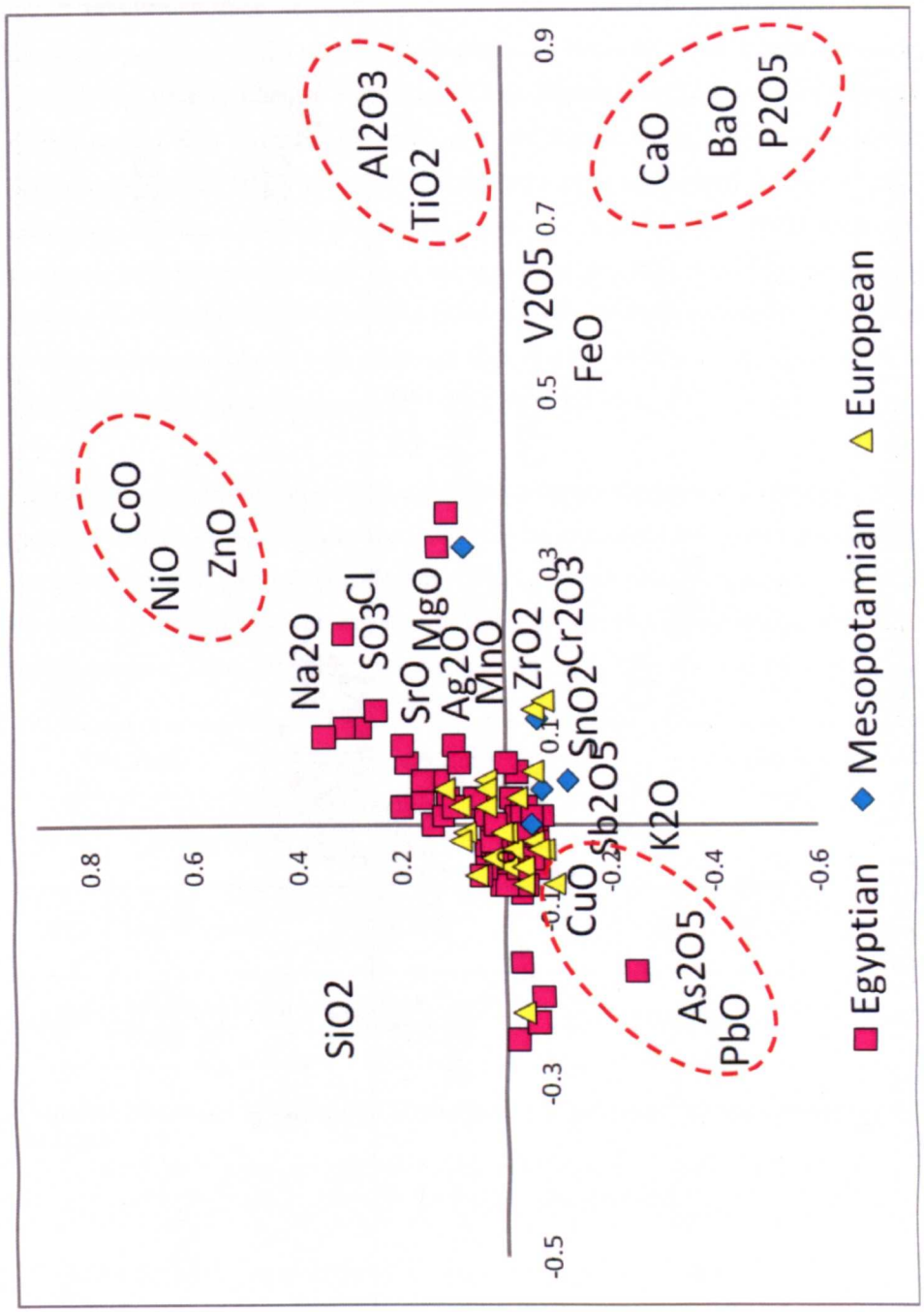

Figure 5.7 Principal Component 1 against Principal Component 2.
For all samples of glass with 97 – 103% of total composition detected by EPMA. Groups of elements and oxides which are suggested, on this basis, to have a strong effect on variation are circled. For ease of reference samples are arranged by region.

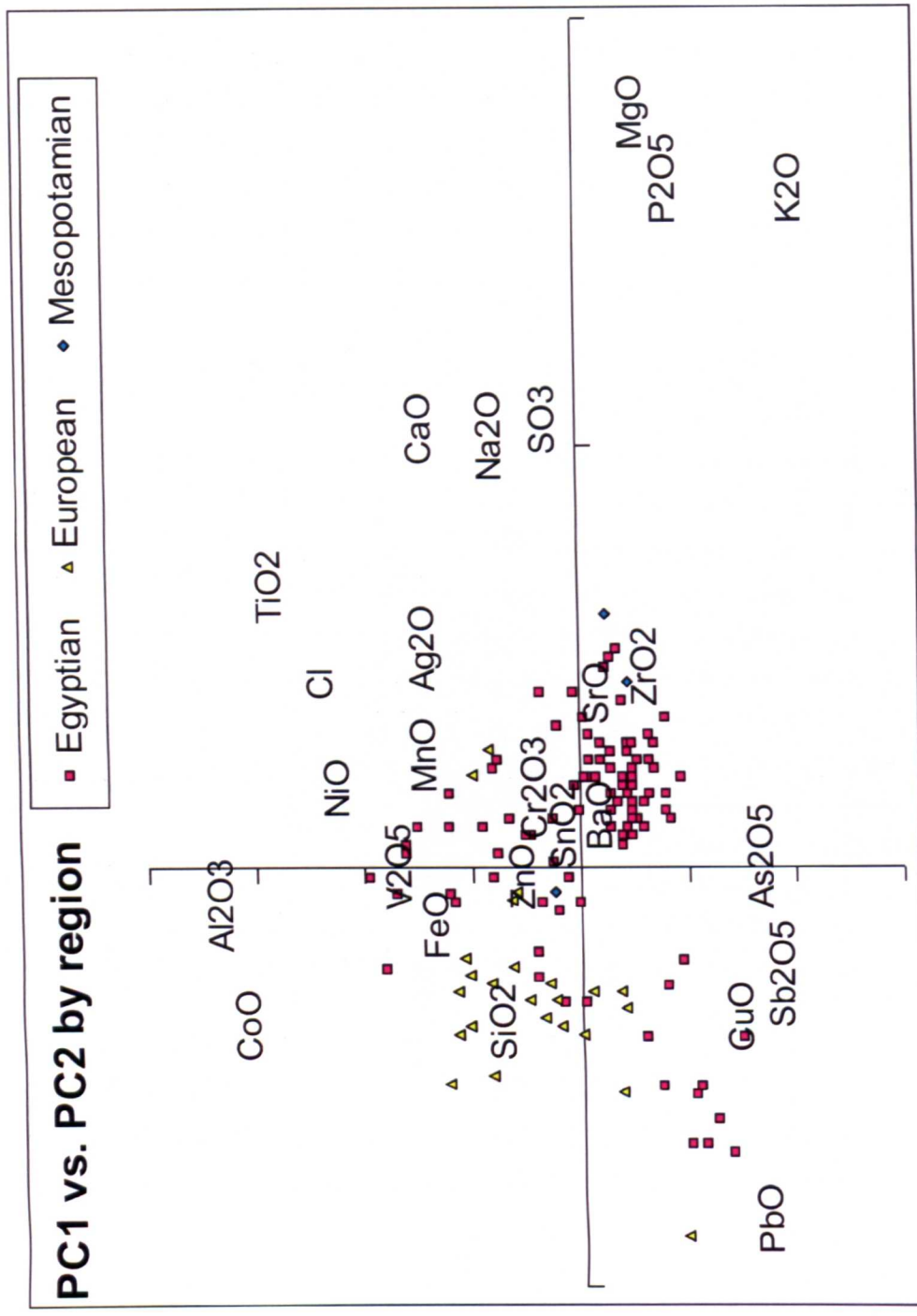

Figure 5.8 Principal Component 1 against Principal Component 2, Arranged by Region.

Third PCA iteration: the plot was produced after the removal of a number of outlying samples, including most of those from Ur. The locations of the elements and oxides indicates the variation they are responsible for.

Alkali Sources

As noted in Chapter 3, the type of alkali used in glass production provides one of the key means of distinguishing between groups of glasses. For ease of reference, Table 5.3 provides a summary of the relevant glass groupings based on alkali source (the reader is also referred back to Chapter 3 and Figure 3.6). Figures 5.9, 5.10 and 5.11 show MgO plotted against K_2O for the glass analysed in the present study, with the data arranged along various lines. HMG and LMG groups have been highlighted in Figure 5.9. The results suggest that almost all of the LBA material is of the expected HMG composition, consistent with the production of glass using plant ashes (see Chapter 3). Three samples from Ur (two dated to 600 B.C. and one listed as Neobabylonian or Persian) were found to form an exceptional cluster with relatively high MgO (3-6%), and – by comparison with other samples and known ranges – very high K_2O (c.4-4.5%).

Probably accounting for some of the distinction between Egyptian and European material apparent through PCA, the majority of the latter falls into the LMG group associated with the use of natron as an alkali (Henderson 1985), as is most clearly apparent in Figure 5.11. So-called LMHK glass, which has been linked to the use of a mixed alkali source defined by Henderson (1988a), may also be represented by one sample, discussed below.

Group		Chemical Characteristics	Alkali Source
HMG	High Magnesia	>2% MgO 1 – 4% K_2O	Plant ash
LMG	Low Magnesia	<1% MgO <2% K_2O	Mineral (natron)
LMHK	Low Magnesia, High Potash	<1%MgO ~7 – 13% K_2O	Mixed alkali

Table 5.3 Summary of Currently Recognised Glass Compositional Groupings Based on Alkali

Only those groupings relevant to the material in this study are listed. Discussion and references can be found in the text in Chapters 3 and 5.

The LMG group shown in Figure 9 contains the following samples and sample groups: Italian 10^{th} – 7^{th} centuries B.C. (sample group 47.1965); Rhodes 900 B.C. (sample group 47.2006); Matmar 3^{rd} Intermediate Period (sample group 32.471); Delos 600 – 300 B.C. (sample group 47.1999); Cyprus 9^{th} – 7^{th} centuries B.C. (sample group 47.2002); three of the samples from Deir 'Ain 'Abata and two of those from Tell Bazi.

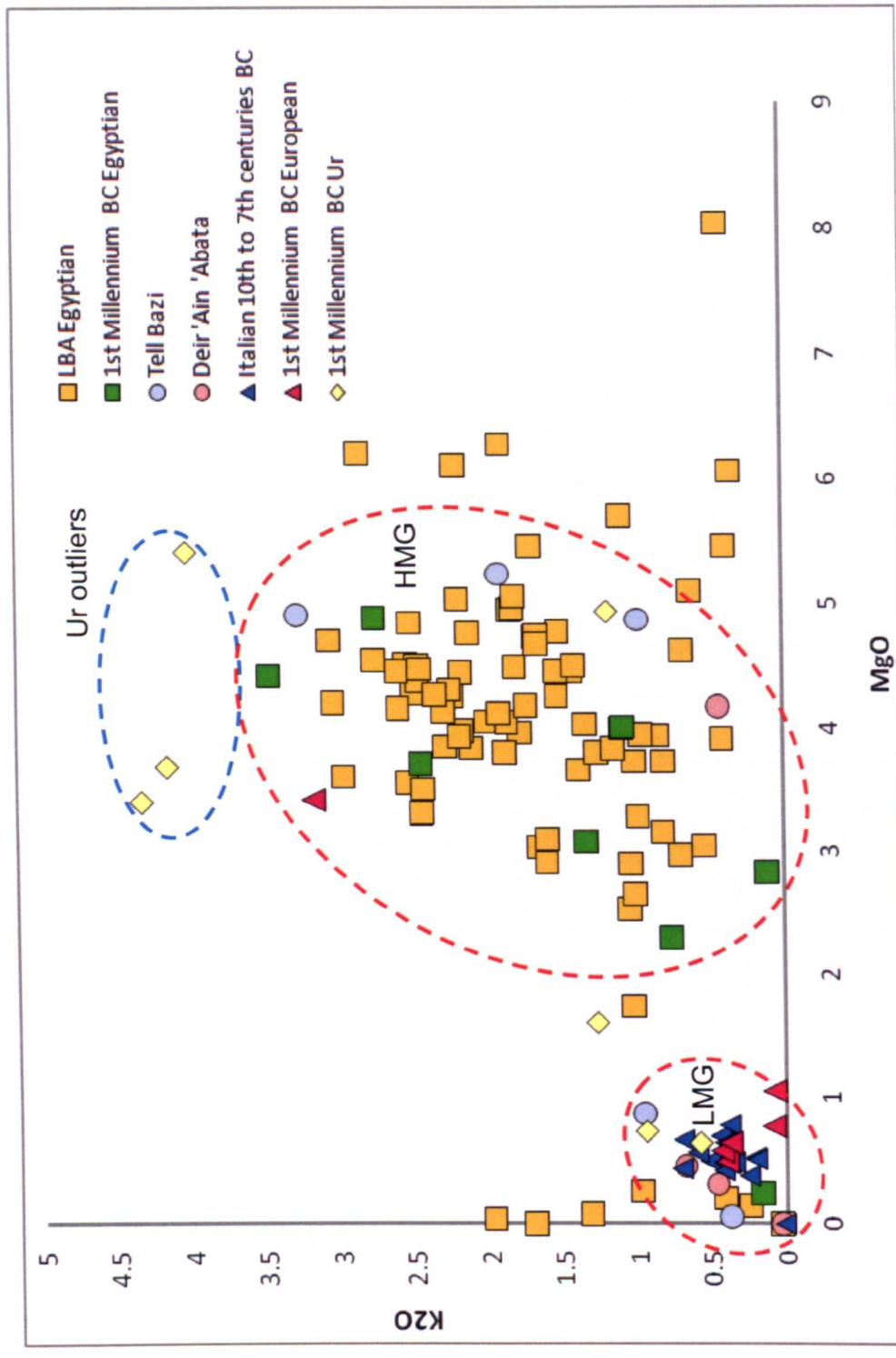

Figure 5.9 MgO against K2O by Weight Percentage.

Arranged by broad date category and find location. Circles showing groupings are based on the data displayed combined with pre-existing categories (LMG and HMG), discussed here and in Chapter 3.

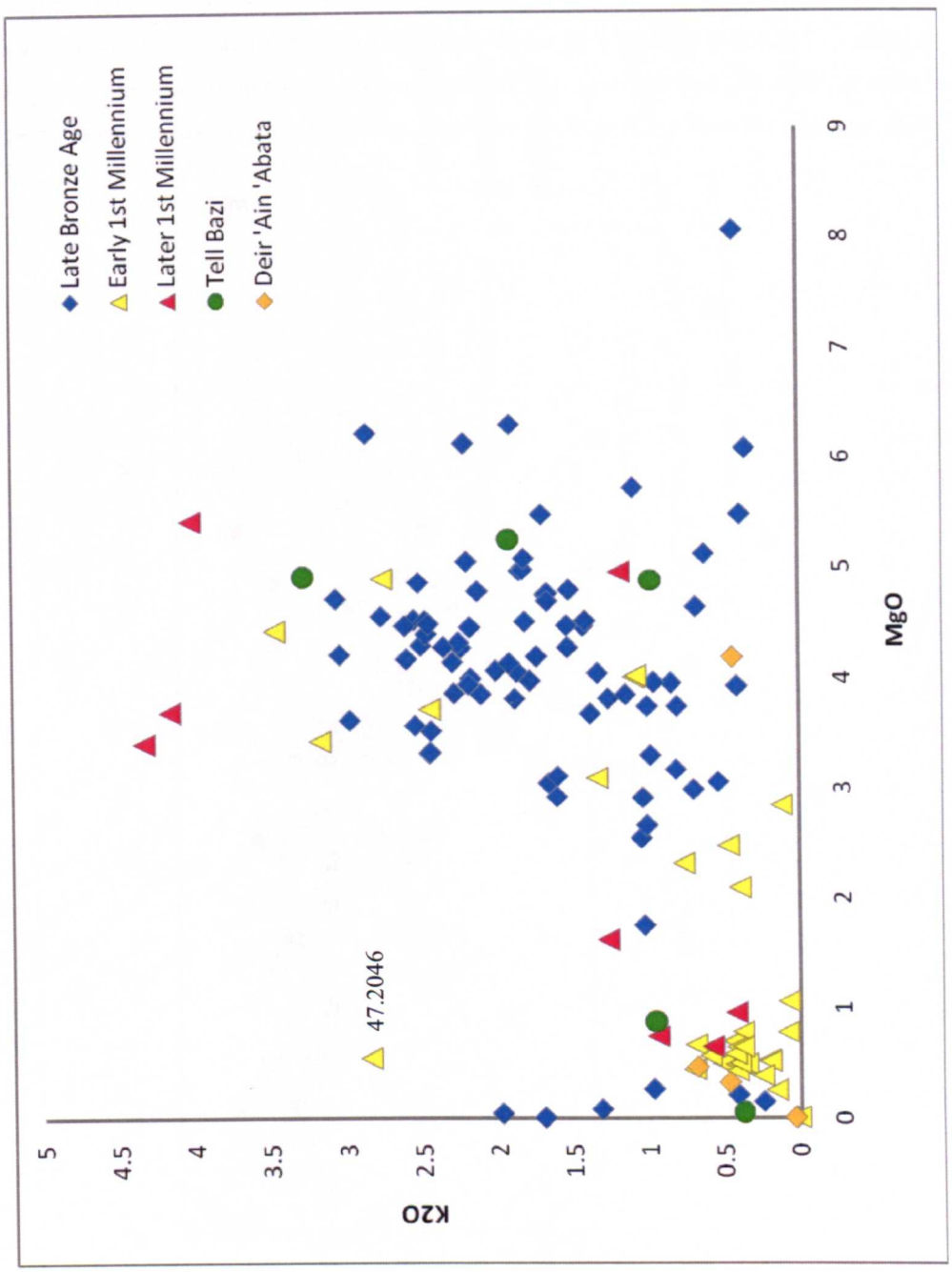

Figure 5.10 MgO against K2O by Weight Percentage, Arranged by Date.

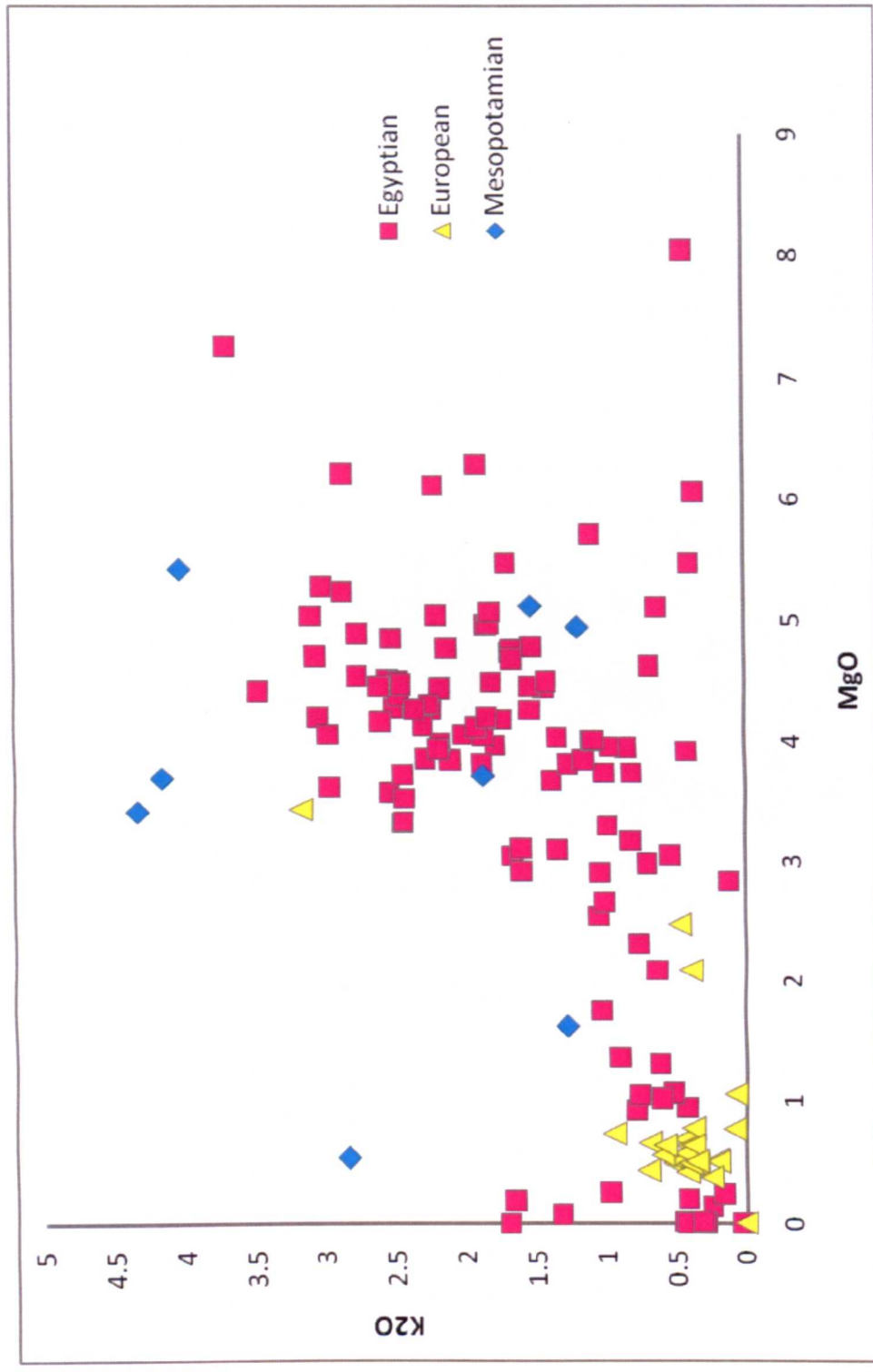

Figure 5.11 MgO against K2O by Weight Percentage, Arranged by Region.

Figure 5.12 illustrates that P_2O_5 and K_2O are directly correlated in all LBA Egyptian and all 'early' (pre 600 B.C.) 1st millennium B.C. samples. The samples from Tell Bazi also fall into this group, as do two of those from Deir 'Ain 'Abata. For several samples dated to the later (post-600) 1st millennium B.C. (47.2082, 47.2133 and 47.2123AB from Ur; 47.1999 from Delos; and 35.1172 from Egypt) P_2O_5 and K_2O are present in similar quantities and ratios as in the LBA Egyptian samples. It is thus likely that P_2O_5 is directly related to the alkali source used, different quantities or ratios stemming from the particular geochemistry of the soils in which the halophytic plants grew, or from the natron used in later glasses.

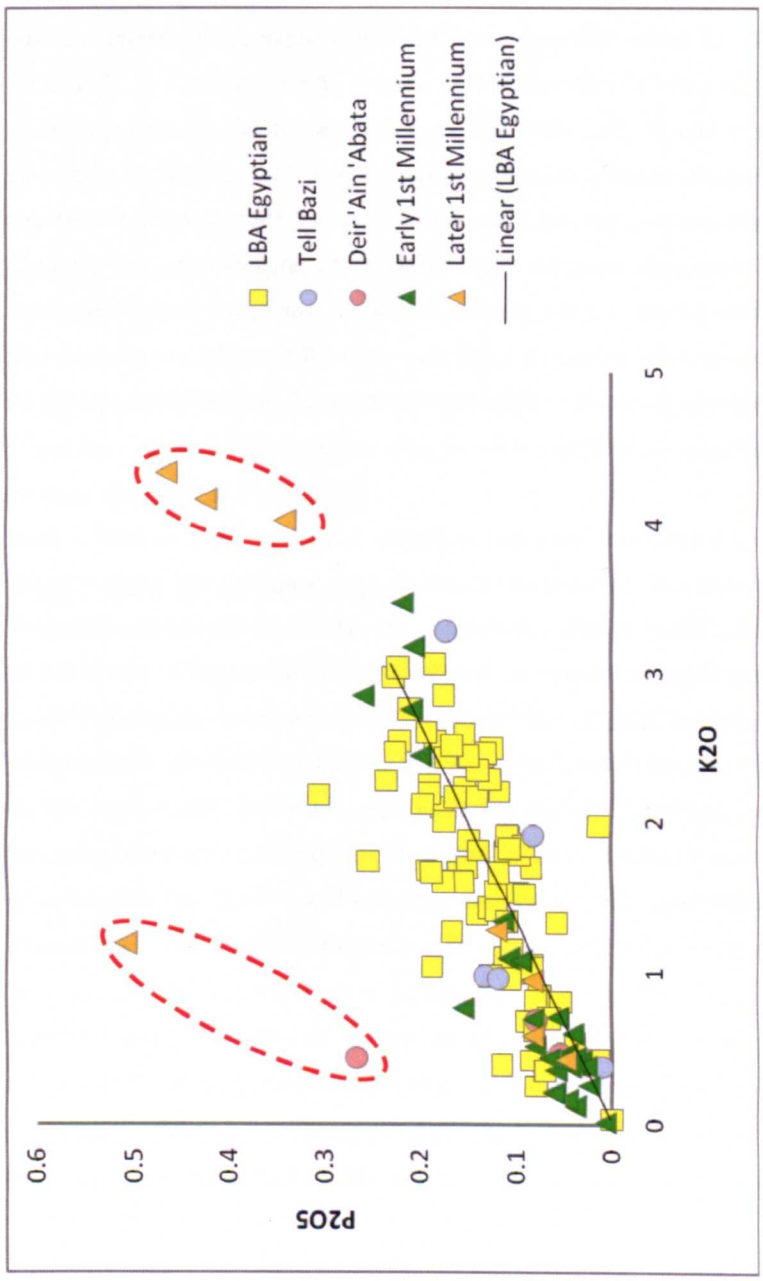

Figure 5.12 K_2O against P_2O_5 by Weight percentage, Arranged by Date.
The trend line is based on the Egyptian samples only, with the intercept set at zero. The dashed circles indicate the position of outliers.

The three samples from Ur dated to c.600 B.C., however, form a separate group with higher P_2O_5 and K_2O. Sample 47.2046 from Ur, discussed below, was also found to fall outside the general pattern for P_2O_5 and K_2O. Barkoudah and Henderson (2006, 311) note that the correlation between potassium and phosphorus tends to break down in the presence of higher levels of K_2O[62], so this may explain the lack of correlation for these samples. The three samples from Ur dated to c. 600 B.C. which have different ratios of P_2O_5 and K_2O are those forming the group with exceptionally high K_2O discussed above and illustrated in Figure 5.9. Interestingly, high K_2O has been linked by Brill (1989, 28) to an Afghan source (based on the composition of plants from Afghanistan). To the best of the author's knowledge, this has not previously been attested in earlier material, so these samples may illustrate an earlier trade of glass out of Afghanistan than has previously been suggested. Another early 1st millennium B.C. sample of glass from Ur (47.2123AB) was found to have very high Al_2O_3, along with high TiO_2, which has also been noted in association with high Al_2O_3 in glass of the Mamluk period, 1171 – 1517 A.D., found in Jordan but thought to have been imported from Afghanistan (see Boulogne and Henderson 2009). Given that these signals seem to relate to plant ash compositions, the possible Afghan source of these Mesopotamian glasses is indeed worthy of further attention, especially when it is considered that lapis lazuli was obtained from the same location at this time: it is possible that glass from Afghanistan was traded along the same routes as the precious stone during the 1st millennium B.C.

Another sample from Ur (47.2046, indicated in Figure 5.10) was found to have a most unusual composition, with low MgO and elevated K_2O. This is commonly associated with LMHK glass, but the K_2O in this particular sample – though elevated by comparison with the LMG group – was somewhat lower (at 3.02%) than the minimum of 5% found in typical LMHK glasses from Bronze Age Europe. This sample also contained elevated Al_2O_3. Aside from the slightly lower K_2O content and elevated Al_2O_3, however, its composition was consistent with that of LMHK glasses, including elevated SiO_2, low MgO and low CaO (see Henderson 1988a, 40). It is thus possible that weathering has distorted the compositional signature of this sample: it was low in Na_2O (1.34%), and only produced a total percentage of 94.52%. This sample was not taken from a well dated bead, but is thought to be from c.600B.C. as it was brought to the Beck Collection along with other material of that date which was also excavated by Woolley at Ur. Its particular compositional features do not correspond fully to any known categories but this may be the result of weathering of a glass which originally corresponded to one of the categories mentioned above. The identification of LMHK glass in wider contexts has been increasing

[62] It should be noted that this research into plant ash composition is ongoing, and the results discussed are expected to be added to in future (Julian Henderson, personal communication).

in recent years (see Nikita and Henderson 2006, 81). A further point to bear in mind is the general potential of beads to travel great distances.

Of the European samples, only the one from Crete (8th century B.C.) does not fall within or close to the LMG group associated with the use of natron as an alkali. It is possible that this sample is a remnant of the trade in glass between Egypt and the Aegean which occurred during the Late Bronze Age (see Chapter 2). Although it is translucent green in colour, however, it was found to contain relatively high PbO (2.4%) and MnO (2.18%) which may suggest that it is a modern intrusion: translucent high lead composition with exceptionally high levels of MnO (up to 8.24%) has been recorded in 19th century samples from Torcello (Andrescu-Treadgold and Henderson 2008).

Some of the blue, LBA Egyptian material with elevated CoO was also found to fall within the region of the 'LMG' group, as is most clearly apparent in Figure 5.10. This is not unusual for Co-coloured glass and the phenomenon has been noted previously (Lilyquist and Brill 1993, 41). Despite earlier suggestions to the contrary, this is no longer thought to be an indication of the use of natron as an alkali source for these glasses (Tite and Shortland 2003, 305 - 307): it is possible instead that this exception to the general reliability of MgO and K_2O as indicators of alkali source may be related to the methods of preparation of the cobalt alums, or even to the use of raw materials specific to cobalt-blue glass, as discussed in Chapter 3.

Regional Distinctions

The relative levels of Al_2O_3 and FeO reveal a distinction based on regional provenance. As illustrated in Figure 5.13, the majority of the Egyptian samples, including those dated to the first millennium B.C., form a cluster with <2% Al_2O_3 and <1% FeO. For most samples, FeO is present at under 0.5%. The European (Italian and Greek) samples have higher Al_2O_3 (2-3%) and more variable levels of FeO whereas the samples from Ur are higher in both FeO and Al_2O_3. As far as can be determined for a relatively small sample set, it appears that the two are broadly correlated in the samples from Egypt and Ur, but that there is a higher percentage in those from Ur.

Shortland et al. (2007, 787 - 788) have suggested that contamination from clay during the production of plant ash may affect the levels of alumina and iron (among other elements), though it is doubtful that clay alone could be responsible for this signature. In addition, recent isotope analyses of Sr and Nd by Henderson et al. (2010) have not shown any evidence of contamination of the silica source.

If the plants which formed the alkali source of LBA glass were gathered from the same location(s) as the sand or quartz used as a glass former, FeO and Al_2O_3 could be brought

in with the plant ashes, the composition of which, as noted above, is largely related to the geochemistry of the underlying soils, which may contain degraded sand or quartz. It is thus not possible to completely distinguish between silica and plant ash related components where this is the case. The lack of correlation with groups based on the distinction between MgO and K_2O, however, suggests that iron and alumina are not related exclusively to the use of different alkalis (i.e. to the distinction between natron and plant ash use). It is thus likely that they are related primarily to the silica source, but that the use of plant ashes which grew in the same geochemical environment would also add to the signal. A small number of the 1st millennium Egyptian glasses which do not fit with the general pattern outlined here may have been imports or have been created using a different manufacturing process. Attempts were made to investigate other possible correlations which might shed light on this situation – such as those identified by Shortland et al. (2007) as belonging to their 'group 2' of trace and minor components (including Zr, Ti and La) – but the detection limits of EPMA precluded any meaningful analysis. What is apparent on the basis of the evidence presented here, however, is that changes over time are in this case less significant than regional compositional differences.

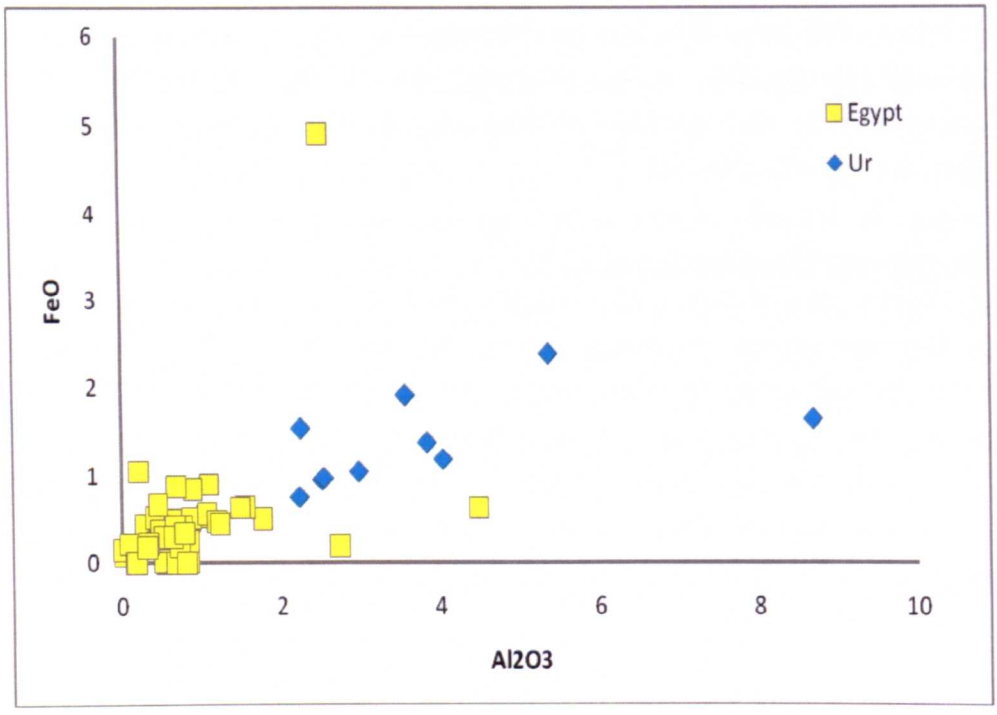

Figure 5.13 Al_2O_3 against FeO by Weight Percentage, Arranged by Region.
Showing only those samples from Egypt and Ur.

All colours of the Italian glass of the 10th to the 7th centuries B.C. which was sampled fall into the accepted region of LMG composition associated with the use of natron as an alkali. Although the completion of the transition to natron is thought to have occurred during the 7th century B.C. (see Henderson 1988a, 441 - 442), there are examples of LMG glass from as early as the 10th century B.C. in Egypt (Schlike-Nolte 2003). The LMG

composition has also been detected in glasses from Minoan Crete, Tell Brak (14th century B.C.) and Pella in Jordan (13th – 12th centuries B.C.) (Nikita and Henderson 2006, 73). Given the evidence for broad regional distinction between the groups (see above), it is likely that natron rather than pre-formed glass was being imported into Italy. This is consistent with other research suggesting an independent Italian glass industry from as early as the 12th century B.C. (see Santopadre and Verità 2000).

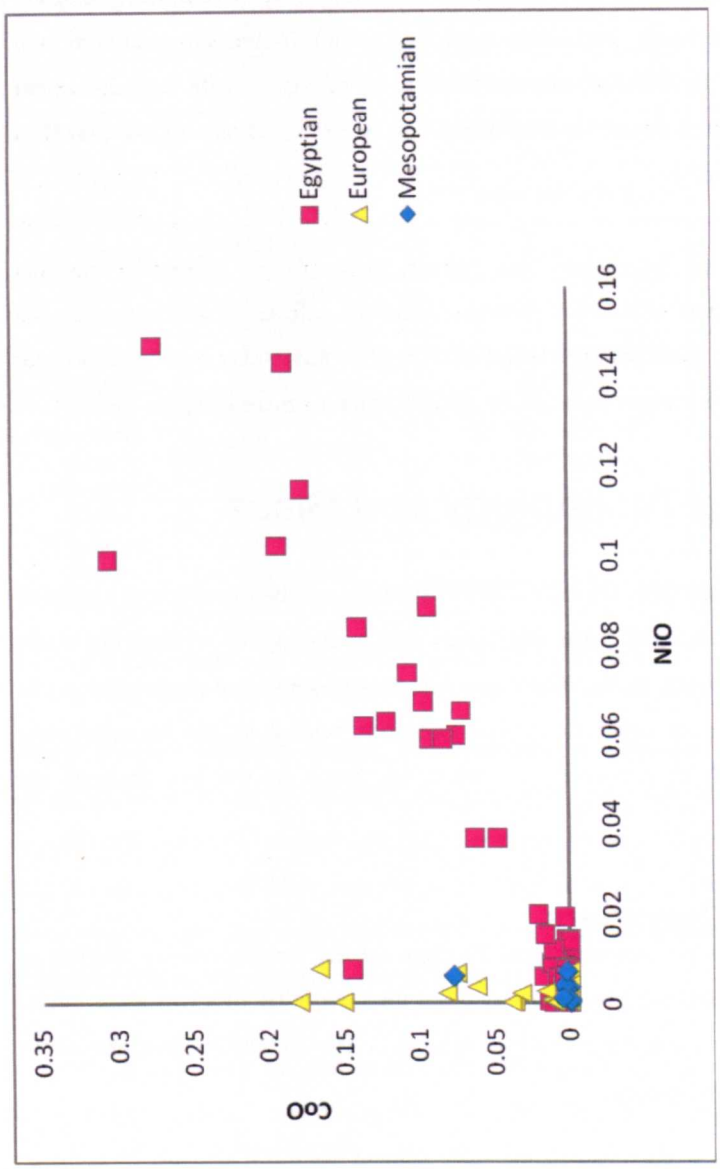

Figure 5.14 NiO against CoO by Weight Percentage for Cobalt-Coloured Blue Glass. A correlation between NiO and CoO is consistent with the use of cobalt alum from the Western Desert of Egypt.

As illustrated in Figure 5.14 all but one (35.1172, dated to between the 8th and 5th centuries B.C.) of the Egyptian samples with significant levels of cobalt fall onto a broad trend line of correlation between NiO and CoO, indicating the use of cobalt alum from the Western Desert of Egypt (see Chapter 3). The turquoise, blue and black samples belonging to the group of Italian glass dated to between the 10th and 7th centuries B.C., however, show no

evidence for the correlation between NiO and CoO. It thus worthy of comment that cobalt was not imported along with natron, given the presence of exploited sources of both in relative proximity in the Western Desert of Egypt. An alternative position, of course, is that some other explanation may be found for the LMG composition, and that natron from Egypt was not used in the production of these glasses.

The samples from excavations at both Tell Bazi and Deir 'Ain 'Abata were severely weathered with the colour being obscured in most, and not all of them returned high total percentages. All samples from Tell Bazi were found to be consistent with Egyptian rather than Mesopotamian material on the basis of their Fe to Al ratio (see above) and may thus represent Egyptian imports.

Three of the four samples from Deir 'Ain 'Abata, however, are plotted in the area associated with LMG glass. It is likely, however, that the effects of weathering on the percentage returned from these samples under EPMA (71 - 83%) may be responsible for this and precludes detailed interpretation of the alkali source for these samples.

Manufacturing Technology and Glass Coloration

As well as providing information on the major constituents of glass production and trace or minor elements associated with these, which may help to distinguish between the nature and source of raw ingredients, as discussed above, it is possible to use chemical analysis and microscopic imaging in order to answer questions related to the manufacturing technology of glass and, in particular, its colouring. Some of the key findings are summarised in Table 5.4.

Colorants and Opacifiers

A brief description of the key compositional findings for the various colours of glass is presented below. This is followed by a discussion of the possibility of a two-stage model for primary glass production, and the evidence relating to more complex questions about recycling and production technology.

Eighteen samples of opaque yellow glass were analysed, of which nine were LBA Egyptian; one was from Abydos (XVIII – XXII Dynasties); four were from Ur; two were Italian and two were from Rhodes. All yellow opaque samples, regardless of date, were suggested by spot analyses of larger inclusions to have been coloured and opacified by the presence of lead antimonate. A different manufacturing technology may have been employed for the production of the later yellow opaque glasses, however, and the Italian samples in particular were found to contain more delicate, feathery or rounded inclusions in contrast to the cubic form inclusions of the Egyptian examples: these feathery forms are

consistent with precipitation from the glass melt[63]. Four samples of opaque green glass were also taken, all of which were LBA Egyptian and all of which were primarily coloured and opacified by copper lead antimonate. These are discussed in more detail below.

Glass Colour Category	Number of Samples Analysed	Colorants, Opacifiers and Morphology	
		LBA Egyptian	Other
Yellow Opaque	18 (9 LBA Egyptian)	Lead antimonate (some inclusions present in streaks)	Lead antimonate (inclusions precipitated from melt)
White Opaque	15 (7 LBA Egyptian)	Calcium antimonate	Calcium antimonate
Turquoise Opaque	17 (10 LBA Egyptian)	Calcium antimonate and copper	Calcium antimonate and copper
Blue Translucent	37 (23 LBA Egyptian)	Copper and cobalt	Copper and cobalt
Red Opaque	1 (Egyptian, post-LBA)	n/a	Copper
Amber Translucent	4 (all LBA Egyptian)	Iron oxide	n/a
Brown Translucent	1 (all LBA Egyptian)	Iron oxide with antimony impurity	n/a
Green Translucent / Semi-Translucent	8 (6 LBA Egyptian)	(See discussion of recycling below)	Iron oxide
Black Translucent	13 (7 LBA Egyptian)	Iron oxide?	Iron oxide?
Purple Translucent	3 (all LBA Egyptian)	Manganese, low magnesia	n/a

Table 5.4 Colorants and Opacifiers Identified by EPMA.
Full descriptions are given in the main body of the text.

Fifteen samples of white opaque, and seventeen of turquoise opaque glass, were also taken. Of these, seven of the white and ten of the turquoise are LBA Egyptian (of the remainder five were 1st millennium B.C. Egyptian, six were European and four were from Ur). All turquoise and white samples were found to be opacified by calcium antimonate, along with copper as a colouring agent in the turquoise samples, as suggested by spot analyses of inclusions and inclusion-rich areas.

A total of thirty seven samples of translucent blue glass were taken. Of these, twenty three were LBA Egyptian. Most contained elevated levels of copper: for all shades of translucent blue and turquoise opaque glass combined, there is an average of 2.6% CuO compared to an average of 0.3% for all other glasses except green opaque. Twenty of the blue glasses contained over 0.05% CoO, and the average CoO content in these was 0.145%. The remainder (including LBA Egyptian samples) were primarily coloured by copper, but as little as 0.05% CoO is thought to impart colour to a glass (see Chapter 3) and even lower amounts – which were present in a large percentage of the samples – may increase the depth of colour in a copper-coloured blue glass. The presence of cobalt may

[63] An example of these has been illustrated earlier in the present work, in Figure 3.8.

indicate its deliberate addition as a colorant: as noted in Chapter 3, the low amounts encountered suggest it was could not have been added in a pure form and the cobalt-bearing alums were probably treated in some way before being incorporated into the glass, accounting for both the variable quantities noted and the low percentages encountered in some of the samples analysed. On the other hand, it is worth noting that other processes may account for its presence in very low quantities (<0.05%). It is suggested here, for example, that a small amount of cobalt could be taken in by halophytic plants if it was present in trace levels in the soil in which they grew. It should also be borne in mind that the presence of cobalt could reflect recycling practices (discussed below).

No samples of blue glass were found to contain SnO, an impurity of which has been linked with the use of scrap bronze to provide a copper colorant for blue glass in the Late Bronze Age (Kaczmarczyk and Hedges 1983). Indeed, SnO was found detected in hardly any of the samples analysed. As it was not detected in the glass standard either, as discussed in the previous section, it is likely that this is a problem with the analytical equipment and cannot be taken as an indication for the lack of SnO in these glasses.

One sample of red glass was taken from a bead excavated at Abydos. The dating of the item is rather broad, and it is listed as falling between the XVIII and XXII Dynasties. It was found to be coloured primarily by copper, with a CuO content of 4.27%. No SnO (which in red glasses has been linked with the use of scrap bronze as a colorant, as noted in Chapter 3) was detected, though this may be related to the sensitivity of EPMA as noted above. Lead, which is associated with the production of bright, 'sealing wax' red glass (Brill and Cahill 1988) was only present as a trace element, at 0.027% PbO.

Also analysed were four samples of amber and one sample of brown glass from Amarna; eight samples of translucent (or semi-translucent: see below) green glass of which six were LBA Egyptian; thirteen samples of black glass of which seven were LBA Egyptian; and three samples of purple glass, all of which were from Amarna. The latter three samples owe their colour to MnO which was present at 0.65 – 0.74%. Two of the samples of purple glass were removed from the same item number (32.412), one from a heart amulet, and these presented unusually low magnesia content for LBA Egyptian glass, with only c.2.5% MgO. This may suggest that this material was produced in a different location to the other colours, or that a slightly different production technology was practised: either way, it is apparent that the glass workers at Amarna were able to obtain a wide range of primary glasses, not necessarily from a single source.

The amber glasses probably owe their colour to a very low percentage of FeO (<0.18 – 0.4%) in combination with SO_3, which can produce an amber colour in glass under oxidising conditions (see Chapter 3). The brown glass has an almost identical composition

to the amber ones, but it was also found to contain a significant impurity of Sb_2O_5 (0.196%), which may have 'muddied' the colour to brown. Alternatively, it is possible that the brown resulted from a different oxidation atmosphere during production. The colour of the black glass may have been caused or affected by the presence of reduced FeO during production. Several of the samples of black glass also contained comparable levels of copper and cobalt to that found in the blue glass, and it is possible that these glasses had been intended to be coloured blue.

Translucent green glass can be produced by Fe present in different oxidation states (see Chapter 3), but the presence of low levels of lead antimonate in the samples of LBA green glass suggests that another process accounts for this colour, which may have been intended to be opaque, as discussed below.

Recycling, Reuse and Manufacturing Technology

Very little published material refers to the question of recycling of Late Bronze Age glass. Recycling has been mentioned in publications dealing with later periods of glass production, in particular those which discuss the use of various isotopes in determining the provenance of raw materials (see for example Henderson et al. 2004; Henderson et al. 2005; Degryse et al. 2006; and Leslie et al. 2006). As noted in Chapter 4, glass from the technological complex at Lisht (1295 – 1070 B.C.) may have been recycled. This was first suggested by Keller (1983) and was later discussed by Mass et al. (2002), who argue that the lower concentration of colorants found in glass from Lisht, by comparison with that from the palace complex at Malkata (1391 – 1353 B.C.) indicates that glass at the former site was recycled (Mass et al. 2002, 76).

It is suggested here that glass mixing cannot be called 'recycling' unless it is clear that preformed glass *objects* were re-melted, since the normal practice was to exchange and re-melt preformed glass ingots and canes. It is argued below that evidence for this practice can be discerned in the compositional and microscopic features of green glass from Amarna. This is followed by a discussion of the probability that mixing or recycling of other colours of glass occurred, and the potential means for assessing this based on compositional evidence.

Green Glass and Evidence for Recycling of Finished Objects

Thirteen samples of translucent (or semi-translucent[64]) and opaque green glass were analysed. Three of these were not LBA Egyptian (47.1965JIII; 47.1995_; 32.471b); the

[64] These glasses were classified as translucent under initial visual examination. The presence of some opacifiers, however, as discussed below, has led to a change of categorisation so that they are now termed 'semi-translucent'. Re-examination has shown

remaining ten are those from Amarna, and of these seven were from glass canes (used for glass working and possibly as trade articles: see Chapter 2). That opaque green glass of the Late Bronze Age was opacified primarily with lead antimonate has already been commented upon elsewhere: it has been suggested that it may have been produced either by mixing two or more pre-formed glasses (see Mass et al. 2002, 75), by adding metallic copper to a pre-formed yellow glass, or by adding a lead antimonate preparation to a pre-formed blue glass (Shortland 2002). The manufacturing processes of yellow opaque glasses are considered in more detail in Chapter 6.

EPMA, however, presents some interesting results which have not previously been considered. The opaque green glasses examined contained lead and antimony oxides, consistent with the view that either yellow glass was used in their production or that a lead antimonate preparation was added in the same procedure as that undertaken for yellow glasses (above). The ratio of PbO to Sb_2O_5 in the green glass, however, was found to differ significantly to that in the yellow opaque: for the yellow opaque glasses analysed the average ratio was 7.7:1, and for green opaque glasses it was 3.12:1.

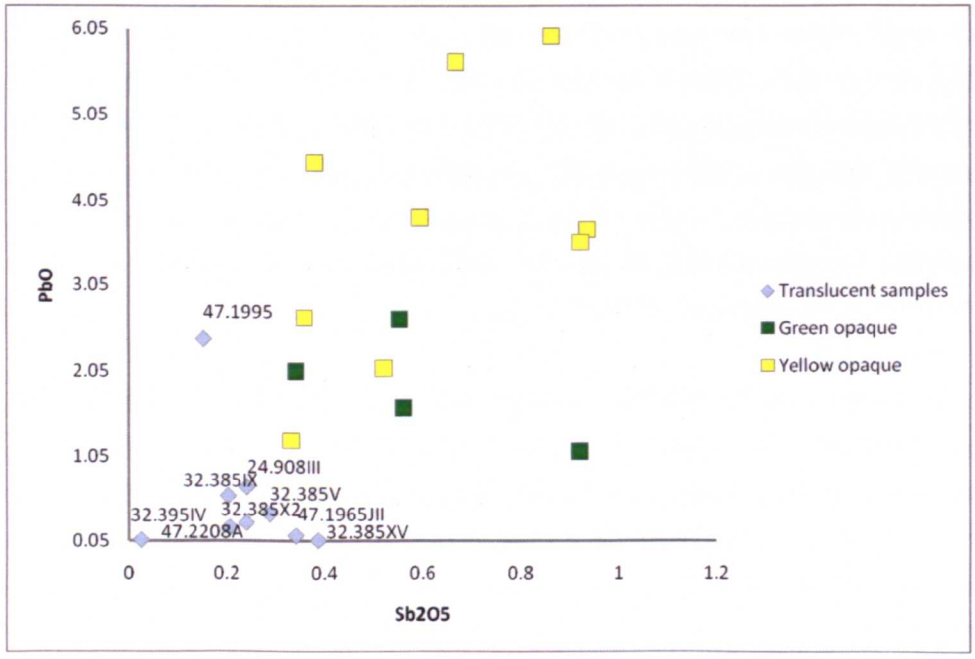

Figure 5.15 Sb_2O_5 against PbO by Weight Percentage, for Yellow and Green Glass.

In absolute proportions, however, the green opaque glasses contain relatively high levels of antimony, close to those found in the yellow opaque glasses. This is illustrated in Figure 5.15. As the figure shows, a similar situation in terms of the ratio of lead to antimony may be postulated for the semi-translucent green glass: the average ratio of PbO

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that their light-transmitting properties remain, but they are rather more cloudy in appearance than other translucent glasses, such as the purple glass from the heart amulet (MAA 32.412).

to Sb_2O_5 in these samples was 2.82:1, which is surprisingly close to the opaque green although the absolute percentages are far lower.

The average Sb_2O_5 content in the LBA opaque white and turquoise glasses analysed here is approximately 2.5 times that found in the opaque yellows, as shown in Table 5.5. If the ratio of PbO to Sb_2O_5 in the yellow opaque (7.7:1) and white opaque (0.04:1) glasses is averaged, the result is 3.9:1 which is quite close to that for green opaque glass at 3.12:1. If turquoise opaque glass is also included this becomes closer still to the average for green opaque, at 2.61:1. The average ratios of lead to antimony are plotted in Figure 5.16: the intermediate position of green glass between yellow and white opaque glass is clearly visible.

Sample Code	Sb_2O_5	Colour	Average Sb_2O_5
32.385VII	1.655	turquoise opaque	2.50959091
32.385VIII	1.025		
32.385XVI	11.48		
32.386IIIvit	0.001		
32.386IV	1.99		
32.386VI	0.914		
Z1184II	3.49		
Z1184III	2.64		
Z1184IV	0.2905		
24.1307IB	1.22		
24.1307IV	2.9		
32.4121wh	2.66	white opaque	2.44733333
32.4122_	3.215		
32.410Awh	3.605		
32.413I2	0.9205		
24.908Iwh	2.54		
47.2469Gwh	1.7435		
32.4121yell	0.9355	yellow opaque	0.96983333
32.4123_	2.44		
32.408I	0.8633333		
32.408II1	0.3595		
24.908IV	0.381		
32.407III	0.3325		
32.377vit	1.38		
24.1307IC	0.6685		
47.2469Eyell	0.52		
47.2477Cyell	1.818		

Table 5.5 Sb_2O_5 and PbO Contents for Late Bronze Age Samples of Opaque White and Opaque Yellow Glass.

As discussed in the survey of colour distribution in finished glass vessels and small items in Chapter 4, yellow and white glass are generally used in roughly equal amounts, and are most commonly found in combination. The next most abundant glass colour applied to vessels and small items was found to be turquoise. Thus, if a typical vessel or small object with a blue base colour was re-melted it might be expected to form a green glass with a similar ratio of antimony to lead as found here. It should be noted that despite the association of lead with calcium in white opaque glasses, the total level of calcium in these has been found to be consistent with that of other LBA glasses (see Shortland 2002, 519 – 522) so calcium does not affect the argument either way.

Considering the apparent inter-changeability between copper-blue, cobalt-blue and opaque turquoise glasses as 'base' colours for vessels and small items (see Chapter 4), the re-melting of a number of fragments containing blue and turquoise base colours along with their applied decoration could result in a similar pattern, with the additional turquoise bodies somewhat counterbalancing the larger volume of non opacified glass contributed by the copper- and cobalt- coloured bodies.

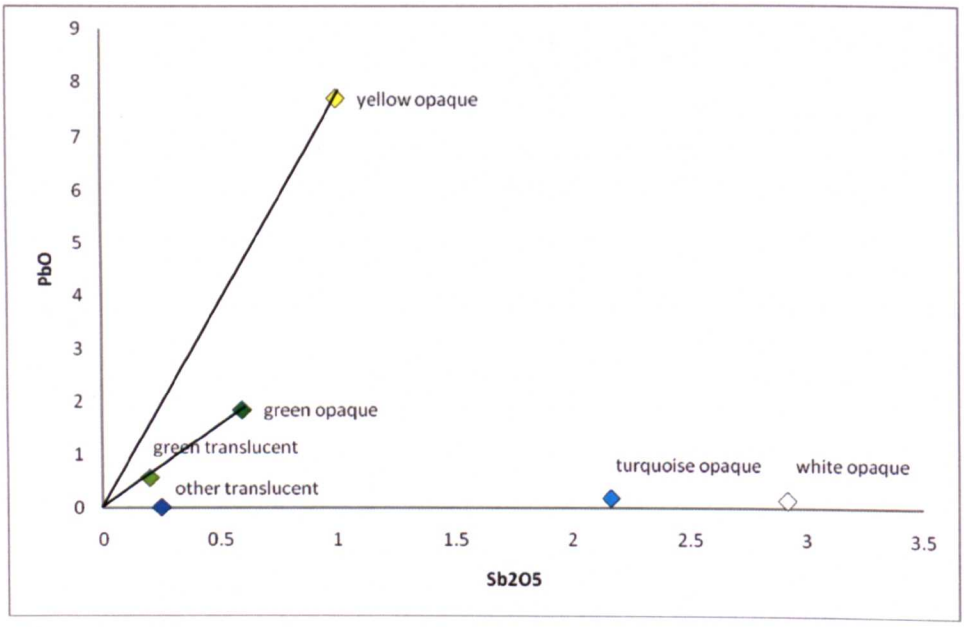

Figure 5.16 Averages of PbO against Sb_2O_5 by Weight Percentage, Arranged by Colour.

Representing 10 samples of turquoise opaque, 7 samples of white opaque, 4 samples of green opaque, and 9 samples of yellow opaque glass. The trend lines represent the average concentrations with the intercept set at zero.

Shortland (2002, 524) suggests that green opaque glasses cannot have been formed through the addition of preformed yellow opaque to another colour of preformed glass because the average copper contents of the glasses he analysed were the same in both copper-coloured blue glasses and green opaques, whereas a yellow opaque glass would supposedly have diluted the amount of copper. In the context of the present study, it was

found that the green opaque glasses, with between 1.091% and 2.04% CuO, contained significantly more than the majority of copper- and cobalt-coloured glasses. The level of CuO was highly variable in all blue glasses, but on average it was only present at 0.51%. Semi-translucent green glasses contained an average of 0.83% CuO, and opaque turquoise an even higher average of 1.18%. It is thus possible that CuO was added to the opaque green glasses, but the variability of that found in the blue glasses makes comparison between the two difficult. In any case, given the difference between Sb_2O_5 and PbO ratios in the opaque yellow and opaque green glasses it is clear that – if a lead antimonate preparation *was* directly added to blue glass in order to make green glass – it was not the same one as was used in the production of yellow opaque. The evidence of image analysis given below, however, suggests that the green glasses analysed here were not formed by the addition of a lead antimonate preparation.

Shortland (2002, 518) also comments on the lack of evidence for the use of cobalt in green, lead antimonate opacified glass. In the context of the above suggestions, however, this can be seen to make sense: even where cobalt blue glass bodies were recycled, the cobalt signal (already present as a low percentage) would be further diluted by the presence of other pre-formed colours of glass.

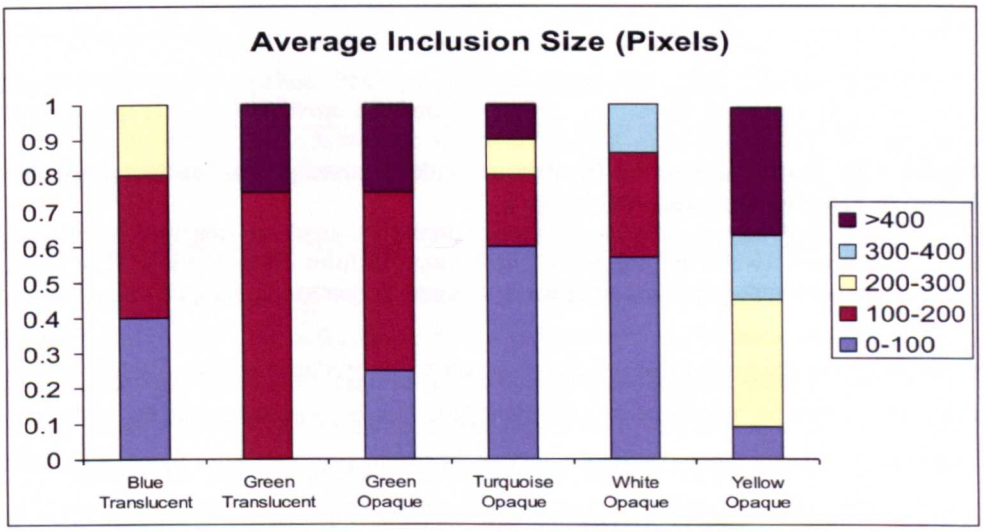

Figure 5.17 Average Inclusion Size for Egyptian Samples Analysed with Image J. Normalised to 100% to account for variation in the number of samples available for each colour of glass. Yellow opaque samples have the highest average sizes.

The results of image analysis also support the 'recycling' hypothesis. As illustrated in Figure 5.17 the average size of inclusions in LBA Egyptian samples is generally greater for the yellow opaque glasses than for white, turquoise and green opaque glasses, and those semi-translucent glasses with some evidence of the presence of opacifiers. The larger inclusion size in yellow opaque glasses corresponds to a lower total number of inclusions by comparison with white opaque glasses, as illustrated in Figure 5.18. The

turquoise opaque glasses roughly correspond to white opaque glasses on this chart. Green opaque glasses, and those semi-translucent green glasses which were found to contain inclusions do not correspond with either white or yellow opaque glasses, but fall somewhere in between with a relatively low total number of inclusions. The total number of inclusions is thus similar to that for yellow opaque glasses, but the size is closer to that of white opaque glasses.

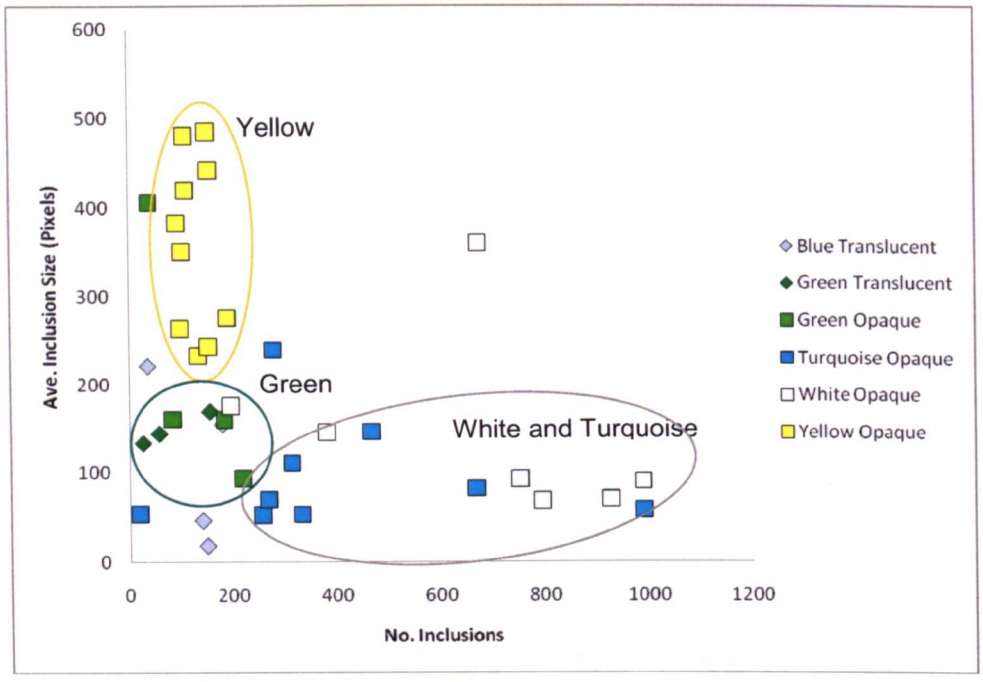

Figure 5.18 Total Number of Inclusions Against Average Size of Inclusions for Egyptian Samples Analysed with Image J.

The yellow opaque samples and those samples coloured and opacified by calcium antimonate (white and turquoise) were found to form distinct groups. The green samples, both opaque and translucent, fall into neither group.

Considering the suggestion that opaque green glass was produced with lead antimonate in the same manner as yellow glass (Shortland 2002) it is interesting that the inclusions found within opaque green glasses do not correspond in size with those found within the yellow (by contrast, the inclusion sizes in opaque white and opaque turquoise / light blue calcium antimonate glasses are directly correspondent). If a lead antimonate preparation was added to blue glass in order to form green opaque, the latter should exhibit similar sizes and numbers of lead antimonate crystals. Instead, the pattern for green opaque glass lies somewhere between that for calcium antimonate and lead antimonate glasses, consistent with the compositional differences noted above. It should also be noted that the inclusions in the green glasses tended to be better dispersed and rounder in form than those in the yellow opaque glasses. This may be a further reflection of precipitation from a melt.

Re-melting of pre-formed glass objects (i.e. recycling) may thus account for the unusual composition and crystal inclusion size of the green glass from Amarna. If we accept that yellow *and* white or turquoise glass were included in the batch, the significant differences in the ratios of lead and antimony between the green and yellow glasses may be explained: additional antimony would be introduced with the calcium antimonate (white and / or turquoise) glass, diluting the amount of lead present.

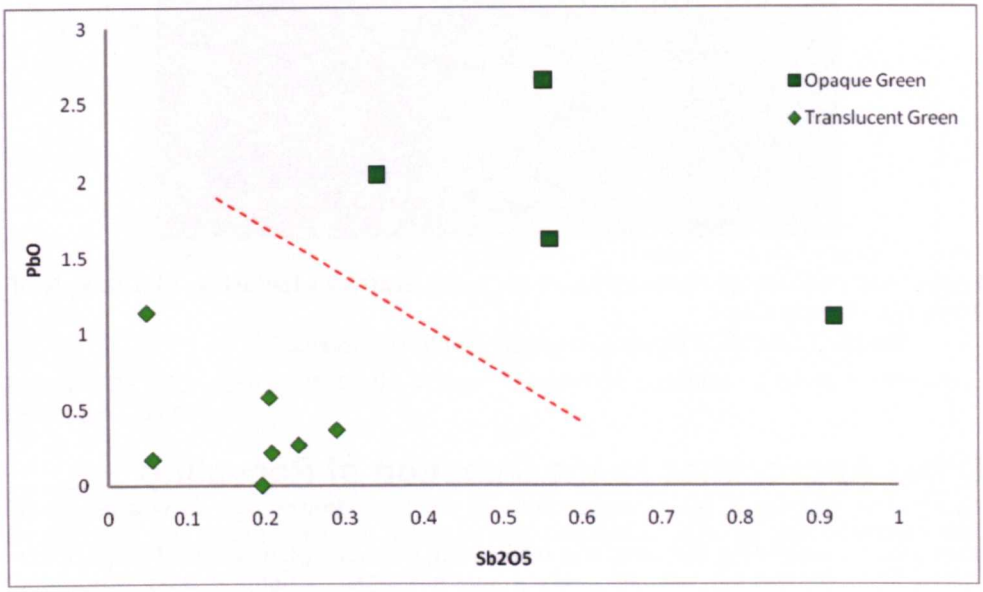

Figure 5.19 Sb_2O_5 against PbO by Weight Percentage, for Opaque and Semi-Translucent Green Glass from Amarna.
The dotted red line indicates the approximate location of the 'cut-off' line between the formation of translucent and opaque green glass.

Finally, the consistency in the ratio of lead and antimony between opaque and semi-translucent green glass may suggest that both were produced using the same ingredients. Figure 5.19 illustrates that although there is a difference in the absolute quantity of lead and antimony present in semi-translucent and opaque green glasses, the approximate ratio of lead to antimony appears to be consistent regardless of the degree of opacity. Figure 5.20 illustrates the presence of small, scattered inclusions in a semi-translucent green glass (though apparently not enough to cause full opacity). It is thus suggested that the ingredients used in the production of the semi-translucent and opaque green glasses analysed here were the same, the major difference between the two lying in the quantities of lead and antimony added to the green glass: those for which the quantity was too low formed a semi-translucent glass. Interestingly, a similar composition for translucent green glasses has been remarked upon by Schlick-Nolte and Werthmann (2003, 30).

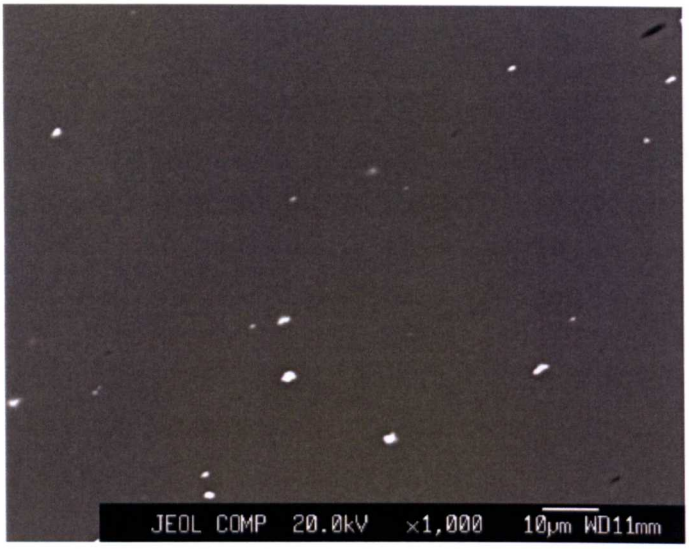

Figure 5.20 BSE Image Showing Small (1–3μm), Scattered Inclusions in a Sample of Semi-Translucent Glass.

Sample 32.385IX, a translucent green glass from Amarna.

Other Approaches to the Question of Recycling

As noted in Chapter 3, glass compositions of the Late Bronze Age show a degree of homogeneity, suggesting that glass was made using a limited, predetermined range of raw ingredients. This may rule out the use of isotopic analysis as the standard 'marker' of recycling, as it is only successful where glasses made from different raw materials (of different geological age) are mixed together. The results presented above, however, indicate that recycling did occur, at least on a limited scale and for the production of green glass. In order to establish whether any evidence for recycling in other glass colours could be discerned, it was decided to examine the percentages of cobalt and associated elements in those glasses not thought to be deliberately or primarily coloured by it. If larger scale recycling of finished items did occur, the presence of cobalt might be expected to conform to the general pattern for LBA glass: that is, the cobalt would be associated with the same elements as in those glasses to which it was deliberately added.

As noted with reference to PCA (above) CoO and Al_2O_3 are associated in the majority of LBA Egyptian samples where CoO is present. In those samples containing CoO above 0.05% – all of which are blue but not all of which were primarily coloured by CoO – NiO and MnO were also found to be correlated, as illustrated in Figure 5.21 (the purple glass contains elevated levels of MnO due to its probably deliberate addition as a colorant, discussed above). As noted previously, correlation between Co, Al, Mn, Zn and Ni is thought to indicate the use of cobalt alum from the Western Desert of Egypt (see also Kaczmarczyk 1987; Shortland and Tite 2000). It may thus be reasonably assumed that these (higher cobalt) samples were deliberately coloured by the addition of cobalt from this source, though the presence of copper will also have affected coloration.

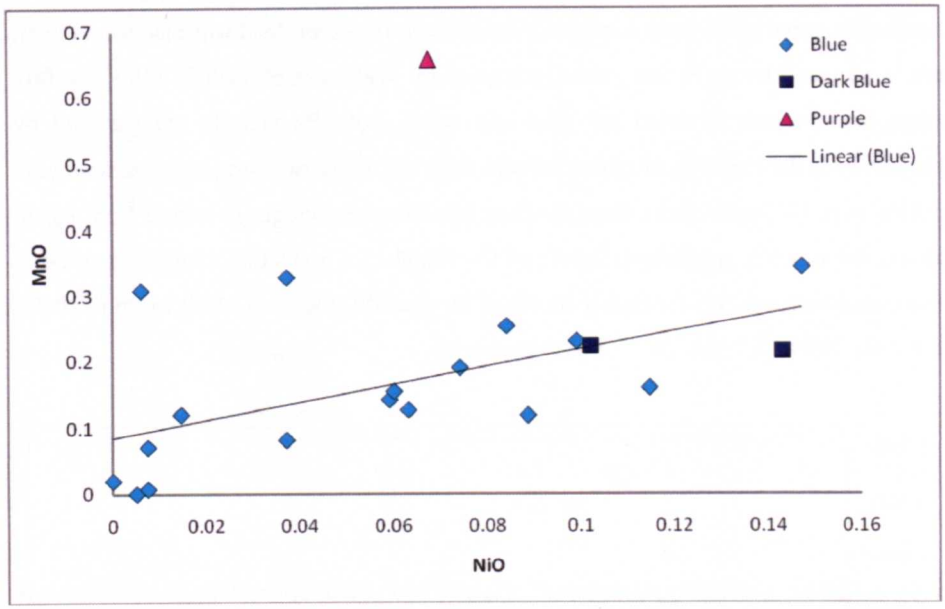

Figure 5.21 NiO against MnO by Weight Percent in Samples of Glass Containing CoO above 0.05%.

As noted above, CoO was also found to be present below 0.05% in a number of samples for which it was not the primary colorant: this includes samples of green (opaque and translucent), blue, turquoise, purple and yellow glass. Because the percentage of cobalt found even in coloured glass is so low, it is difficult to assess whether a correlation between Co, Ni and Mn exists due to the fact that these are present in far lower amounts initially, and are closer to the detection limits of the electron microprobe. Figure 5.22 illustrates the levels of CoO and Al_2O_3 – which are present in higher quantities than NiO and MnO and thus more easily assessed by EPMA – in glasses containing very small amounts of CoO. This relationship is difficult to assess, however, because Al_2O_3 is also related to other raw materials, as discussed above. Although for most samples the quantity of ZnO was also too low to determine whether it could be found to correlate with CoO, one sample of light blue and one sample of purple glass with slightly elevated CoO fall into the same group (with reference to the ratio of ZnO to CoO) as those thought to be deliberately coloured by the cobalt alum, as illustrated in Figure 5.23.

Because trace element analysis was not conducted, it was decided to use published results of this in order to ascertain whether any evidence for recycling could be discerned based on the model presented above. In a study using LA-ICP-TOFMS to examine trace elements in blue Mycenaean glass (thought to derive from both Egypt and Mesopotamia) from the J. Paul Getty museum and excavations at Tiryns, Walton et al. (2009) refer to elevated quantities of antimony in order to suggest this may have been added deliberately as an opacifier (Walton et al. 2009, 1499). The quantities detected, however, are too low to suggest complete opacification, and the rarity of opacified blue glass in these contexts

indicates that these are unlikely to be failed attempts to do so, as has been suggested above for translucent green glass from Amarna. Interestingly, however, lead was also found to be present in elevated levels in the glasses analysed by Walton et al. (2009, 1499 – 1500). Although the amounts detected are relatively small, both Pb and Sb are elevated by comparison with the majority of trace elements detected. Only two samples contained both Sb and Pb over 1000ppm: these were the only two samples thought to derive from Egypt which did not contain appreciable levels of Co (2004.15.5 and 2004.15.6, J. Paul Getty Museum) and both contain far higher levels of Sb than Pb (the ratio of Sb to Pb is 10.5:1 and 8.1:1 for 2004.15.5 and 2004.15.6 respectively).

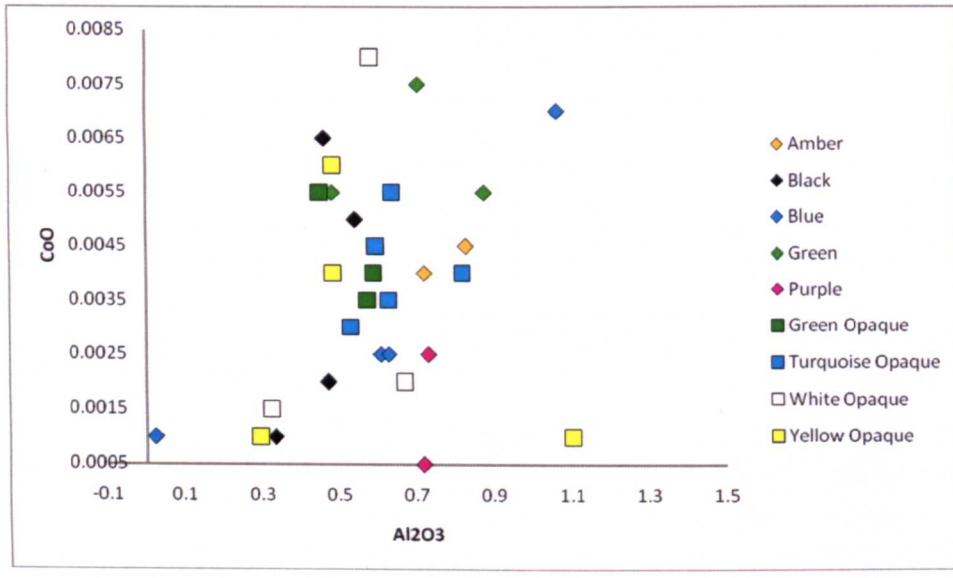

Figure 5.22 Al_2O_3 against CoO by Weight Percent, Showing Various Colours of Late Bronze Age Glass with Trace Levels of CoO.
Not all samples are visible on this scale.

It is suggested here that the presence of elevated antimony and lead in these copper coloured glasses may be related to the addition of preformed glass, in the standard colour repertoire of the time (which includes small amounts both calcium- and lead- antimonate opacified glasses as discussed above). The lack of evidence for this in the Mesopotamian material coupled with the results presented above may suggest that the practise was more common in Egypt.

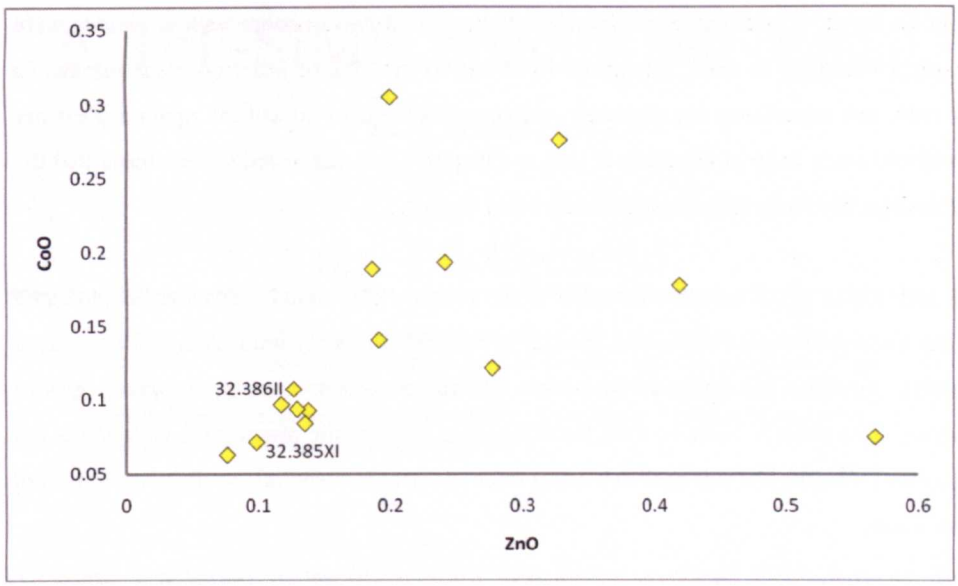

Figure 5.23 ZnO against CoO by Weight Percentage, Showing Samples of Late Bronze Age Egyptian Glass Containing over 0.05% CoO.
Most of the samples were taken from blue or dark blue glass, but two of those with lower levels of CoO and ZnO were from purple glass (32.386II) and light blue glass (32.385XI).

Discussion

However difficult it may be to approach, the question of recycling should not be ignored in studies of glass production and it has important implications for our assessment of technological choice and value. Some points for consideration are suggested here, and the issue is considered in the broader context of this study in Chapter 7.

Henderson et al. (2004, 459), with reference to experimentation and change in Islamic glass compositions, note that recycling would have been a key factor in the identification of working properties of the glass. The compositions and working methods of the Bronze Age may be different (though both, of course, are made with plant ashes) but it must have been understood that particular colours, notably opaque yellow and red, were prone to certain changes on heating and working, not least the danger of affecting the colour, or the strength / brightness of the colour through oxidation (red glass) or overheating and oxidisation (yellow glass). In any case, the addition of significant amounts of glass coloured or opacified by lead or cobalt would significantly affect the successful production of all but the most robust colours of glass (due to contamination from these stronger colouring or opacifying agents).

Large-scale recycling, therefore, was probably not practised, and the few Nd and Sr isotope results available (see Henderson et al. 2010) do not indicate the mixing of glass from different regional sources. Possible LIA evidence of this has been noted for a yellow glass rod from Amarna (see Shortland 2006, 667), but in this case the practise involved

might be better termed 'mixing' since it is thought that two or more yellow glasses were mixed, presumably in 'raw' unworked form due to the lack of other colorant signals. In any case, the manufacturing processes and possible sources of yellow opaque glass are considered more fully in Chapters 6, and in Chapter 7 it is suggested on this basis that the lead isotope evidence may be affected by other factors.

The addition of small amounts of cullet to the primary glass batch, however, as indicated by the trace presence of numerous species associated primarily with colorants (discussed above), cannot be ruled out at this stage. Perhaps more importantly, the green glasses analysed here seem to indicate that, for this colour at least, the practise of recycling is not out of the question. Further research using trace element is essential for the clarification of these issues.

A final point should be made in relation to production processes and colouring. The idea of a two-stage production process for Late Bronze Age glass, noted previously in Chapters 3 and 4, has also been put forward by a number of authors (see for example Shortland and Eremin 2006, 592; Shortland 2002; Mass et al. 1997; Bimson and Freestone 1983). The main problem with this hypothesis is the lack of archaeological evidence for the intermediate, uncoloured glass. Two crucible fragments with adhering coloured glass from Lisht are discussed by Rehren (2000a, 19): in both examples a layer of colourless glass was found between the coloured glass and the crucible wall, suggesting that in some cases at least (and it must be remembered that the material from Lisht is relatively anomalous within the context of LBA glass production) the practices of glass making and glass colouring were distinct. Similarly, Shortland et al. (2007) suggest, with reference to LA-ICP-MS study of trace elements in 54 samples of Egyptian and Mesopotamian glass that there exists a 'base' Egyptian glass composition which is detectable through the removal of those oxides associated with coloration. Unfortunately, their study was only based on blue and colourless glass, so that the question of whether the two-stage model is feasible for all glass production remains.

A two-stage production model, however, would be consistent with varied methods of producing colour: if the process of colouring is removed from that of primary glass production, the complexity of producing different colours may be more conducive to fine tuning and manipulation of various ingredients without the added concern of successfully producing a fully formed glass. Furthermore, if primary glass production occurred in larger batches than glass colouring (which involves the limited dimensions of crucibles, discussed in Chapter 2), the addition of small amounts of cullet to aid glass formation would be less likely to have an effect on the colour, and this could account for the low levels of colorant associated with so many different colours of glass.

6. ToF-SIMS: opacity and crystal formation

6.a. Background

> "Today Static SIMS is considered to be one of the most important techniques for surface analysis. A number of unique features like the detection of all elements ... the isotope sensitivity, the molecular information and the extremely low detection limits, makes it quite different from Auger Electron Spectroscopy (AES) and Photoelectron Spectroscopy (XPS)."
>
> Alfred Benninghoven 2001

ToF-SIMS is a variety of the Static SIMS techniques, developed specifically for high resolution surface analysis. It is uniquely capable of performing compositional mapping and semi-quantitative to quantitative analysis on the first few atomic layers of a sample with submicron spatial resolution.

The present work may be taken as the continuation of a pilot study of the use of ToF-SIMS for the analysis of ancient opaque glasses initiated by Julian Henderson, Frank Rutten, Martin Roe and David Briggs (see Rutten et al. 2009; Rutten et al. 2006; Rutten et al. 2005). Their primary research has been built upon and the main difficulties encountered have been met with and – I hope to demonstrate satisfactorily below – largely resolved in the present study. The scene is now set for a larger scale study using ToF-SIMS to investigate ancient opacified glasses, following as closely as possible the methods and practices outlined here. Due to the quantity of information derived from the use of ToF-SIMS, the results of the present study merit some discussion in their own right, and can already contribute to debates about LBA glass production.

A brief summary of the suitability of ToF-SIMS for the study of ancient glass is provided below. Following this is a description of the theoretical background to the technique. In the subsequent section a detailed exploration of the methodology employed in the present study is presented. This is felt to be necessary due to the novelty of the technique in the analysis of archaeological material (the pilot study is the only previous archaeometric use of ToF-SIMS). Although the publications associated with the pilot study also provide some discussion of methodology, many of the experimental parameters have been altered since the initial programme of study, and some of the problems encountered there have now been resolved.

Why Use ToF-SIMS for the Analysis of Ancient Glass?

ToF-SIMS is the only currently available technique which is capable of chemically analysing and mapping major, minor and trace levels of components on a small enough scale to provide detailed information on the composition within the opacifying agents found in ancient glass (Rutten et al. 2009). Almost all archaeological examples of opaque glass owe their opacity to the presence of very small particulate inclusions within the uniform glass matrix, as discussed in Chapter 3.

The shallow depth profiling of ToF-SIMS (discussed in further detail below) allows the composition of individual particles to be determined. Because the emitted ions measured by this technique originate only from the top few atomic layers of the sample surface, any particulate inclusions bisected by the sampling technique will be mapped alongside the bulk glass matrix, without the danger of also including information originating from the homogeneous material beneath the inclusions. The technique provides mapping of internal composition of inclusions and their spatial relation to one another, allowing the detailed examination of the nature of the inclusions themselves. ToF-SIMS also has the capability to detect all elements present, can give information on compounds, and can determine the presence of isotopes, all of which data can be presented in images with sub-micron resolution and including trace elements present in quantities as small as 0.5 – 5ppm (Rutten et al. 2009, 966).

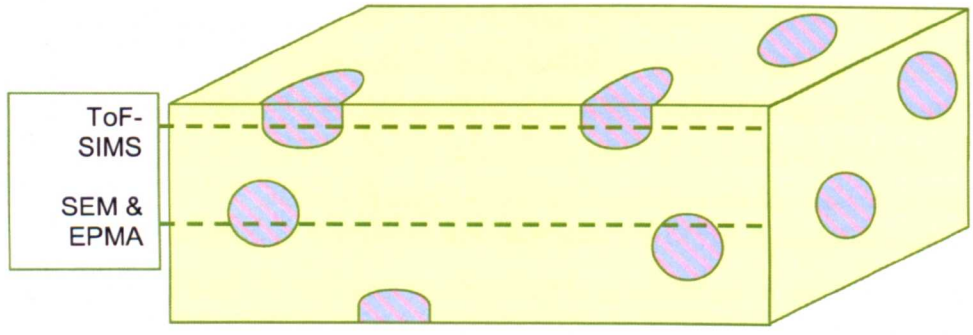

Figure 6.1 The Depth of Analysis of ToF-SIMS Applied to Opaque Glass.

Although other techniques such as SEM can provide distributional information, their lower sensitivity (100 – 1000 times less sensitive than ToF-SIMS) renders the detection and mapping of trace elements impossible. ICP-AES and LA-ICP-MS are capable of this level of sensitivity, but the distributional information is lost. Similarly, though detailed images of glass opacifiers can be achieved using a number of techniques the depth resolution of such techniques is typically too poor, so that the glass matrix below an inclusion will also be analysed: precise results on the composition of the inclusion and the distribution of elements in and around it cannot thus be achieved (Rutten et al. 2005, 25): this is illustrated schematically in Figure 6.1. A comparison of the depth and lateral

resolution capabilities of ToF-SIMS with a number of analytical techniques is illustrated in Figure 6.2.

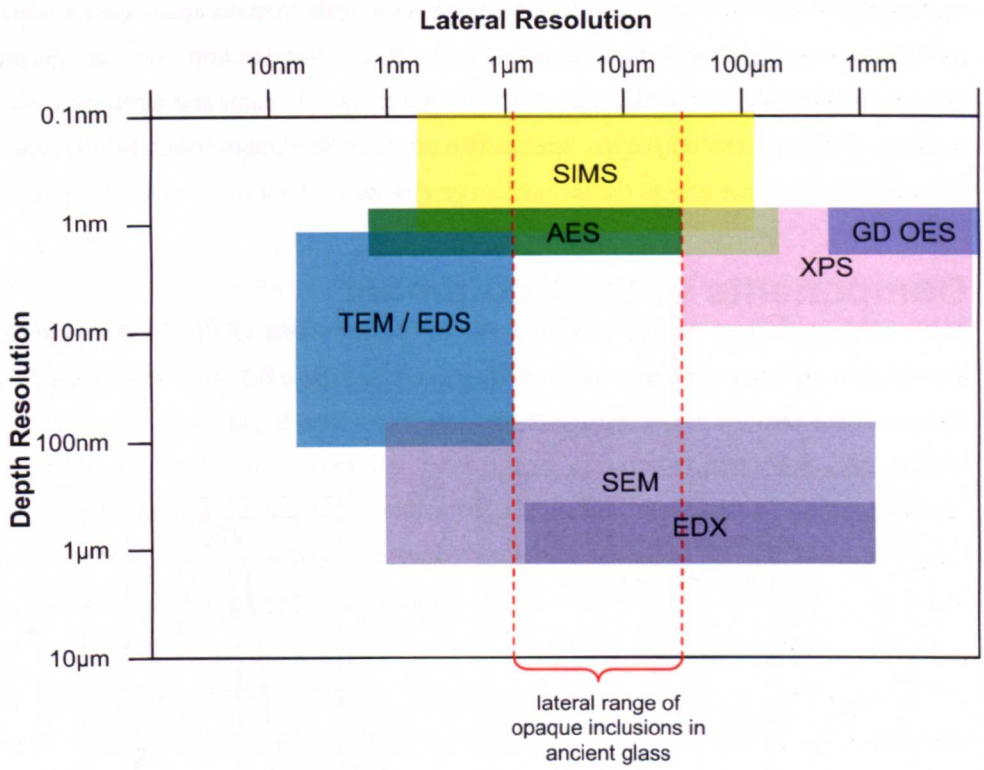

Figure 6.2 Lateral and Depth Resolutions of Selected Analytical Techniques.

Furthermore, ToF-SIMS provides spectra for the chemical make-up of any one area within an image. The primary ion beam can be highly focused, allowing a spatial resolution of <1µm in imaging mode, when the ion beam is digitally rastered over the surface (Rutten et al. 2005, 26). Such experiments are best carried out using the raw data stream (RDS) approach, discussed below, in which the full spectrum is acquired at each image pixel: this can then be used to generate a total ion image by summing the intensity at each pixel, the contrast in the image being dominated by topographic (here negligible as the samples are sectioned and polished) or major chemical differences so it provides a useful visualisation of the scanned area. The potential for the characterisation of isolated regions within a sample is thus provided, crucially with the aid of high mass resolution data.

Basic Theory of ToF-SIMS

The basis of ToF-SIMS is the bombardment of a sample surface by a high energy beam of (primary) ions in order to cause the sputtering (emission) of secondary ions and neutrals deriving from the sample material itself. Of these secondary, emitted species ionised species (elements and compounds) are detected and measured by the mass spectrometer.

When the high energy (typically 15 – 25 keV) beam strikes the sample surface, energy is transferred to the atoms of the solid sample causing a 'cascade' of collisions between the

atoms, as described in more detail below. Some of these ultimately return to the surface and result in the sputtering of atoms and atom clusters, a proportion of which are ionised on leaving the surface (for a more detailed description of the process see Urbassek 2001; and Garrison 2001). Over 95% of the secondary particles detected originate from the top two monolayers of the sample, and although atomic species can have larger sampling depths (up to 5nm) than polyatomic species (Rutten et al. 2009, 968) the collision process dictates that only those near to the surface can be ejected.

Components of the Equipment

The main components of the ION-TOF SIMS IV Instrument (ION GmbH, Münster, Germany) used in the present study are illustrated in Figure 6.3. Key elements of the equipment and analysis procedure are discussed in more detail below.

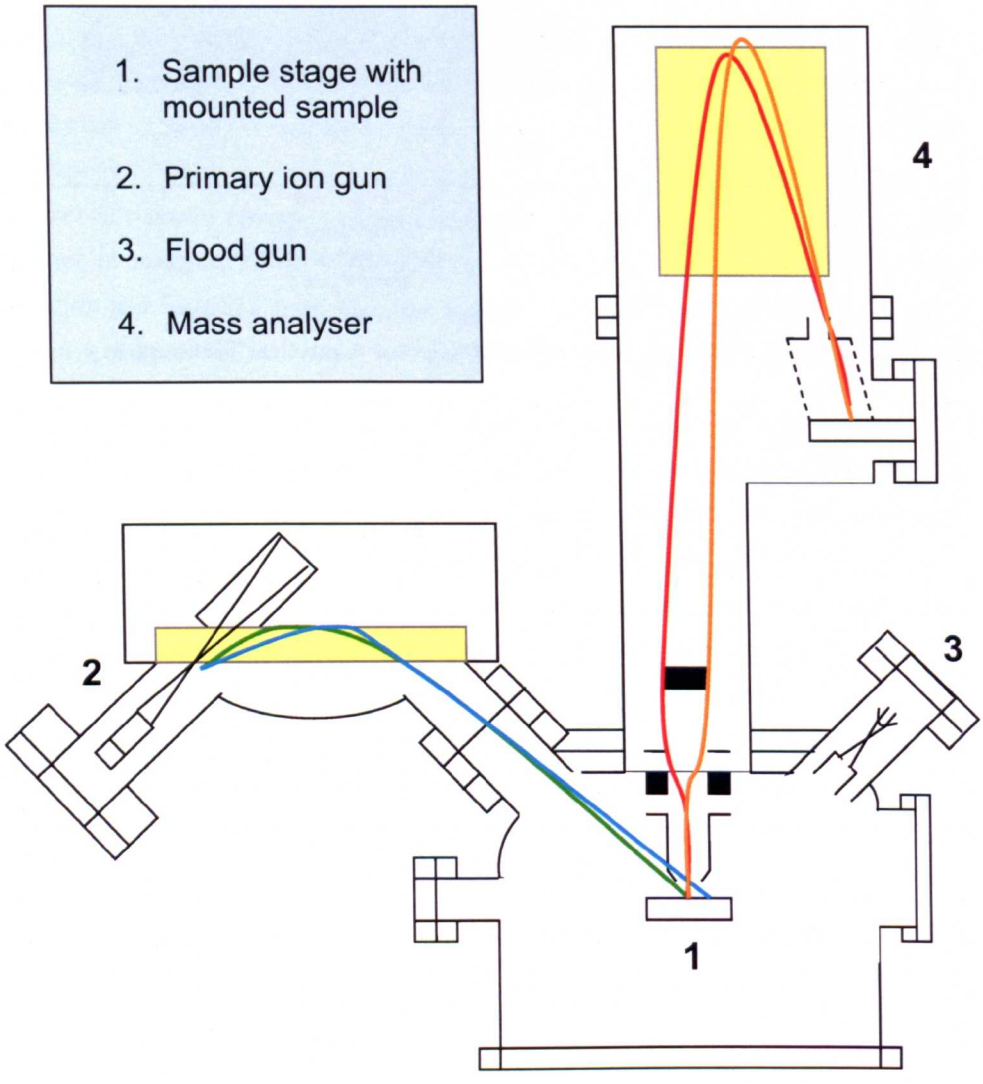

Figure 6.3 Schematic Representation of an ION-TOF IV Instrument.
After Gilmore 2001, 262.

Primary Ion Beam

The primary ion column is mounted at 40° to the sample surface normal, delivers a beam from a mono-isotopic source and can be pulsed with a pulse length at the sample surface varying from less than 1ns up to several μs: brief pulses provide high mass resolution (high current bunched, or HCB, mode), while longer pulses provide higher spatial resolution (burst alignment, or BA, mode) (Vickerman 2001, 12). The beam flux can also be varied to prevent detector saturation.

The most commonly used ion sources until recently were of the liquid metal ion gun (LMIG) type, of which gallium was the most frequently employed (Hill 2001, 95). Although a Ga LMIG was used during the pilot study, the equipment has since been upgraded and a Bi-cluster source was used in the experiments described here. The use of polyatomic (cluster) ion sources has been shown to improve secondary ion yields, especially for organic materials, by comparison with monoatomic primary ion sources as a result of the higher energy density of polyatomic species (Van Stipdonk 2001, 309) and the spread of the energy between the atoms making up the polyatomic species. Because this produces a larger impact crater, however, the surface sensitivity is slightly reduced where polyatomic sources are used. The negative effects of this are minimised in the present study as sputtering above the static primary particle dose limit[65], required for depth profiling, was not necessary. Perhaps more significantly, the inclusions analysed in the present study almost certainly extend deeper into the sample than even the 5nm limit noted above (otherwise they would not have been as visible in SEM).

Time of Flight Mass Analyser

The ToF mass analyser provides parallel ion detection, so that the masses of all ions ejected as a result of primary ion impact can be detected without re-tuning the instrument to the detection of a particular mass (Schueler 2001, 92). After the primary ions hit the sample surface, the secondary ions are accelerated from the surface to the ToF analyser by a 2.5keV extraction field into the secondary ion optics which consists of a large bore, high transmission two-element lens. Flight time is measured by further accelerating pulses of secondary ions to a given potential (3 to 8 keV) through a field-free drift tube (Rutten et al. 2005, 26). Mass separation thus occurs, with the lighter ions arriving first at the detector: according to the equation of kinetic energy, for ions of the same charge and with the same kinetic energy, heavier masses travel more slowly through the drift tube and so the measured flight time, t, of ions of mass to charge ratio, m/z, accelerated by the same potential V down a flight path of length L provides the means of mass analysis:

[65] 'Static' conditions are those that maintain the integrity of the surface layer within the time-scale of the analytical experiment. The calculation of the static limit takes account of the fact that each impact physically influences an area of $10nm^2$ which implies 10^{13} impacts cm^{-2} to influence all the atoms in the surface (see Vickerman 2001, 5 – 7). For organic materials consisting of larger molecules, sometimes rather sensitive to ion-induced damage, this limit can be as low as 10^{12} ions per cm^{-2}.

$$t = L[m / 2zV]^{1/2} \text{ [5]}$$

The flight times of all the ions are electronically measured and can be related to known ion mass by a calibration procedure described below, allowing the generation of a mass spectrum of all the ions present. Positive and negatively charged ions must be collected separately (see Rutten et al. 2009, 968): where both are required (as with the work presented here), the experiment must be run twice.

Flood Gun

Glass, as an insulator, requires charge compensation to prevent the bombardment of primary ions from raising the surface potential of the sample and causing the kinetic energy of the emitted samples to rise beyond the acceptance window of the analyser (Vickerman 2001, 9). Charging is almost entirely due to the formation of secondary electrons (SEs) on primary ion impact, which escape the sample surface leaving it positively charged. The flood gun thus provides surface charge stabilisation through sending a pulsed beam of low energy electrons, typically <20eV to the sample surface between the secondary ion extraction phases (Gilmore 2001, 269): the electrons are attracted to the region of positive charge on the surface, returning the surface potential to neutral.

Theory of Secondary Ion Generation

In the simplest approach to understanding sputtering the atoms can be regarded as hard spheres obeying Newtonian mechanics. Sigmund's linear cascade theory has been the most successful model of the sputtering process so far. It assumes that sputtering occurs by particle bombardment at small incident particle current and fluence (Vickerman 2001, 15). Sputtering events are classified into knock-on sputtering and electronic sputtering. Electronic sputtering is negligible for ToF-SIMS as used here, and the knock-on, 'billiard ball' model is sufficient for this explanation.

The theory is developed on the basis of elastic collisions between particles. In this process the incident particle transfers its energy to the target atoms and thereby initiates a series of collision cascades between the atoms of the solid within about 30 Å (0.003μm) of the surface. Some of these collisions return to the surface and cause the emission of sputtered particles, as illustrated in Figure 6.4. Only approximately 1% of emitted particles are ionised and can be measured by the mass analyser.

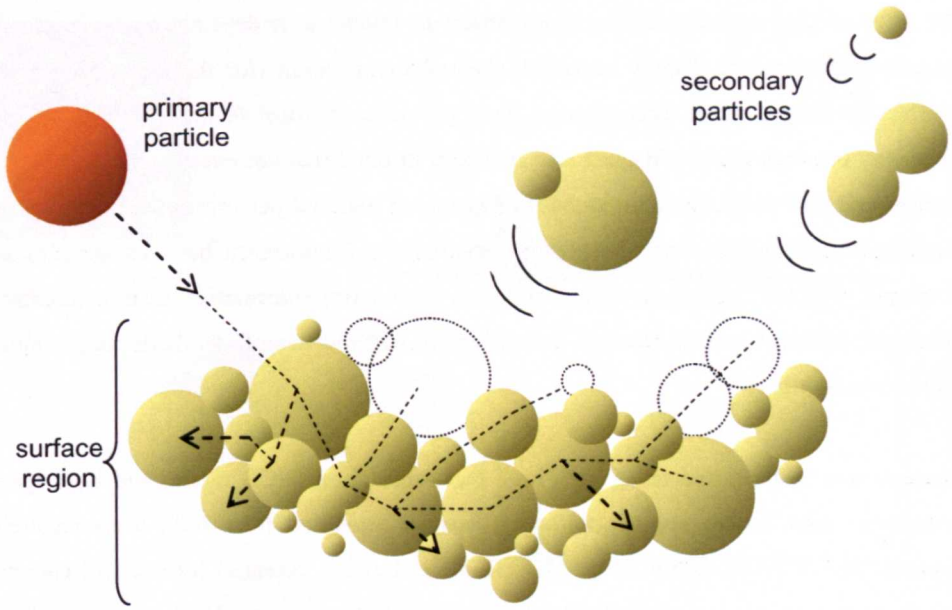

Figure 6.4 Schematic Illustration of the Basic SIMS Process.
After Vickerman 2001, 1.

Identification of Spectra

Identification of spectra obtained through ToF-SIMS analysis relies on a measure of manual interpretation, albeit aided by reference spectra[66] and basic chemical knowledge of the stoichiometry and relative abundance of isotopes. One reason that manual interpretation is still such a strong feature of SIMS work is because of the enormous wealth of detailed information it provides: the complex information retrieved from whichever species are present in a solid material can in some cases preclude the measurement of separated identifiable elements due to mass coincidences within the attainable mass resolution of isotopes, hydrides, oxides and hydroxides in particular. In any SIMS apparatus, all the species within the sampling depth contribute to the spectrum. The specific procedures are outlined in the methodology provided in the following section.

Image Analysis

The ION-TOF mass analyser is capable of relatively rapidly collecting and storing images which contain the full mass spectrum at every image pixel. Thus data can be gathered and interpreted or reconstructed at a later date using the dedicated software. For a typical 256 x 256 pixel image, there will be 65,536 distinct mass spectra, each of which may contain hundreds of ion peaks (Tyler 2001, 475). Images are presented using a thermographic intensity scale, which ranges from black at zero intensity through red, orange and yellow to white at the maximum intensity for that particular ion (Rutten et al. 2009 970). It should

[66] The reference spectra used were the Static SIMS database and data saved from previous studies using the equipment at the University of Nottingham. In some cases it was necessary to add species to the existing spectra, following careful consideration of factors described below.

be stressed that intensity differs from image to image as it depends on the particular threshold required to display variation: the maximum count (for the most intense spot within an image) which accompanies them provides an absolute method of comparing intensity between images. It must also be borne in mind that not every element or indeed compound will yield the same amount of sputtered material per primary ion impact, and ionisation probabilities can also differ considerably. Comparison between samples and between selected regions within samples is thus more informative than comparisons between different species (though quantification and the use of standards may improve this comparability).

Images can be produced using both high mass resolution (HCB mode) and high spatial resolution (BA mode) spectra. Although images generated from high mass resolution spectra do not reveal as much spatial definition, they are essential for detailed chemical analysis regions of interest (ROIs) within the sample (see below). High spatial resolution images are useful for revealing the detailed distribution of elements and compounds across the area analysed, but the less clearly resolved peaks from which these are generated means that element assignments within them must be carefully checked against the high mass resolution data. It is essential to cross-reference the high mass and high spatial resolution spectra and the images generated from these in order to fully understand the detailed chemical composition of matrix and inclusions.

Raw data files created during the primary ToF-SIMS analysis contain a spectrum for every pixel in an image, typically mapping 80-100μm^2. The summed data shows the intensity of all compounds, etc., for the entire mapped area. Because the raw data is linked to individual pixels, however, it is also possible to isolate a ROI within a larger image and view the summed data for this area as a single spectrum, as illustrated in Figure 6.5: the image on the left shows a 256 x 256 pixel area of a sample, saved as a raw data (.raw) file. A spectrum is produced showing the signal from the area as a whole (top right, modified (.dat) file). Alternatively, individual pixels or groups of pixels can be isolated, and separate spectra produced for these (shown in the bottom right). Including a larger number of pixels significantly improves the detection limit as lower abundance and harder to ionise elements and compounds are summed, while isolating a ROI allows the identification of weaker signals only present in a particular area of a heterogeneous sample (and can help to reduce the amount of peak contamination by signals of similar mass). Thus while some species cannot be visually mapped, their presence or otherwise can be unequivocally determined and (potentially) quantified.

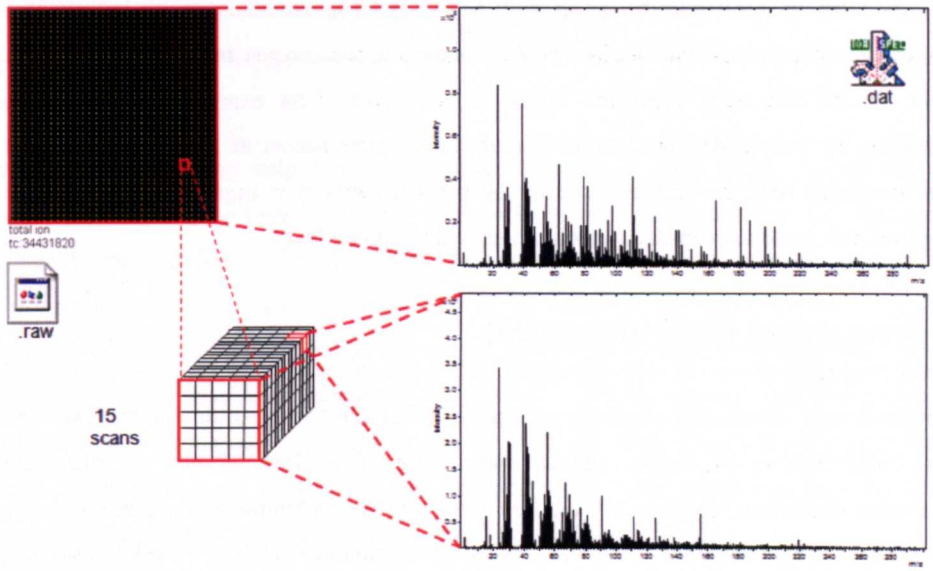

Figure 6.5 Spectra and Pixels in Primary ToF-SIMS Data.
Image reproduced with the kind permission of David Scurr, School of Pharmacy, University of Nottingham.

Background to the Application of ToF-SIMS to the Study of Ancient Glass

An example of the chemical mapping capabilities of ToF-SIMS and their application to archaeological glass is shown in Figure 6.6 for positive secondary ions. The area shown in the images is 80μm^2. The presence of each element is mapped separately with brighter areas indicating higher abundance.

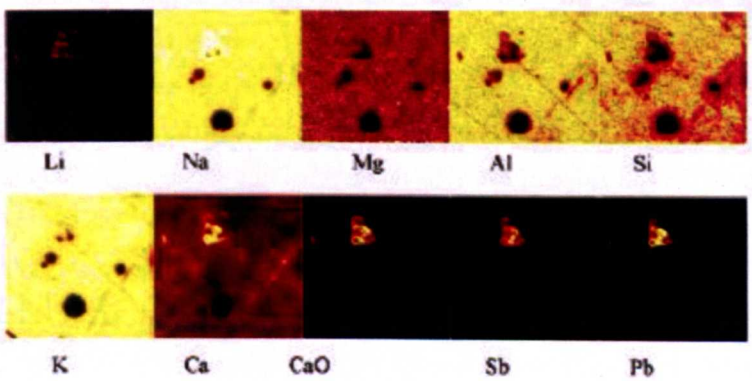

Figure 6.6 Example of Elemental Mapping in ToF-SIMS.
Positive ion results for high spatial resolution mode, with elements assigned by reference to high mass resolution spectra. Area: 80 x 80 μm^2.
From Rutten et al. 2006, 7125.

The matrix of the glass in Figure 6.6, as expected, is richer than the inclusions in Si, Na, Al and K. Ca is clearly present in both the matrix and the inclusion, although CaO is richer within the inclusion. The inclusions also contain elevated levels of Pb and Sb. Li (which

as a light element is difficult to detect with SEM) and Mg are also present but are less preferentially distributed. The darker spots on several of the images and especially clearly visible on the Na map, represent holes in the glass. This example illustrates the capabilities of ToF-SIMS for detailed distributional information at a surface level, but when compared with the images used in the present study it is hoped the value of the improvements made to preparation techniques will become clear.

Approaching Quantification

Absolute quantification is not necessary in order to establish the co-location of heterogeneously distributed elements within glass but relative quantitative analyses can allow better testing of results against each other. ToF-SIMS is not an inherently quantitative technique, and was not used as a quantitative technique in the present study. Its potential for quantification, however, has been experimented with in the pilot study and shown to have been successful (see Rutten et al. 2009; and Rutten et al. 2006, 7125 - 6). Although ion yield can vary considerably due to sputter yield, ionisation probability and matrix effects, and peak intensity is thus not inherently related to the concentration of the species that it represents, it should be noted that in the course of the experiments described below, the relative intensities can be taken as indicative of some real difference in concentration between samples as well as within samples, given the similarity of the matrix and the experimental parameters applied to all four samples analysed. This is supported by comparison between the relative quantities of major components (Si and Na) which are strongly correlated across the samples analysed.

Avenues of Data Acquisition

As outlined above, there are a number of methods for data acquisition using ToF-SIMS. As well as the potential to gather and combine separate data for both positive and negative emitted ions, the analyst can choose to focus on high mass resolution or high spatial resolution images and / or spectra. Each of these tools can provide a powerful array of information on the full range of elements represented in the sample, and a high degree of information related to chemical speciation. The most valuable asset of ToF-SIMS, however, is the ability to combine all of these elements in a single study. As outlined in the rest of the present chapter, this approach provides a set of results which relies on cross-referencing and checking these datasets against each other, offering far more information than the sum of their constituent parts.

6.b. Method

Since the pilot study into the investigation of ancient glass using ToF-SIMS was conducted, there have been a number of changes to the instrumentation and equipment available for ToF-SIMS. The present study has also attempted to reconcile some of the early problems, delays and other issues raised by Rutten et al. (2009; 2006; 2005). New methods of optimising the location of areas of interest and reducing the time spent on the instrument itself have been developed and tested. It has also been found that particular materials and techniques for sample mounting must be used. The methodology has thus been presented in some detail here, and it is hoped that it can stand as a basis for future research into ancient glass opacification with ToF-SIMS.

Instrument

The ToF-SIMS instrument used in these analyses is located in the School of Pharmacy at the University of Nottingham, funded by EPSRC through the Strategic Equipment Initiative. It is a ToF-SIMS IV from ION-TOF GmbH of Münster, Germany, equipped with a Bismuth cluster ion source for spectroscopy and capable of imaging at a spatial resolution of better than 100nm. The reflectron ToF mass analyser has a mass resolution in excess of 10,000 m/δm.

Sample Preparation

An initial set of samples was prepared for analysis in 2007, and these were mounted in cold-setting epoxy resin, ground and polished as described for EPMA in Chapter 5. The resin blocks were then cut to size (13 x 13 x 3 mm) and mounted on flat metal plates of a suitable size for insertion into the SEM sample holder. Their edges were covered with aluminium tape and their surfaces carbon coated to avoid charging during their initial examination using SEM. After SEM had been conducted they were removed from the metal plates, briefly polished using 1μm diamond paste on a rotating polishing wheel and cleaned in a sonic bath (isopropanol) in order to remove their carbon coating with the minimum possible effect on the surface features seen under SEM. They were wiped with a lens tissue dipped in high-purity hexane directly before insertion into the ToF-SIMS sample chamber to remove any relict siloxane contamination: polydimethylsiloxane (PDMS) is much used in a range of plastics and cleaning products and tends to form a thin layer which can significantly impede secondary ion signals from the surface under investigation.

The initial sample set, however, could not be analysed with any success: hydrocarbon PDMS was found to be present on the sample surfaces under ToF-SIMS investigation. The sample was duly sputtered with 3KeV Argon ions in order to remove it. This was

tried first on the sample edge and then in the centre of the sample. In both instances the PDMS was found to return, its presence interfering strongly with the spectra generated from the sample surface itself. The PDMS returned too rapidly to allow spectral analysis or imaging to be undertaken of the actual sample. It was noted, however, that the PDMS signal became elevated more quickly at the sample edge than the centre and it thus seemed to originate from the resin itself, probably due to slow diffusion from the latter (Frank Rutten, personal communication). It is therefore likely that the cold-setting resin used for this initial experiment and commonly used for embedding samples destined for analysis with electron microscopes is unsuitable for SIMS work: the resin likely contains low levels of highly mobile PDMS which diffuses onto the sample. Whereas such a signal would be negligible under an electron microscope, the very high surface sensitivity of ToF-SIMS means that even slight surface contamination features strongly on the secondary signal detected.

As it is not possible to dissolve the cold-setting epoxy resin used, it was necessary to source a new set of samples and repeat the preparation stages using a different resin. In order to avoid the risk of contamination, a hot-setting Araldite CY 212 resin (Agar Scientific) was used: this is harder and the heat treatment renders it more stable, although its use has largely been replaced in recent years by cold-setting resins due to their ease of preparation. In a fume cupboard, the Araldite resin and a DDSA hardener were measured in syringes to 20ml and 22ml respectively and heated to 60°C along with a clean conical flask. They were then added to the warmed flask and this was gently rotated by hand until they were combined. The prepared resin was poured into moulds containing the samples and hardened for 24 hours at 60°C. The subsequent stages of preparation, before and after SEM analysis, followed the same path as described for the cold-setting resin above.

Some hydrocarbons were found to be present on the surface of the Araldite-mounted samples, but these were removed to a satisfactory degree by sputtering (see below) and this particular Araldite is thus recommended for future ToF-SIMS work.

SEM Investigation

Analyses were conducted on a JEOL 6400 SEM with EDX, located in the Department of Mechanical, Materials and Manufacturing Engineering, University of Nottingham. In order to successfully utilise the time available on the ToF-SIMS equipment itself, SEM investigation of the mounted samples was undertaken to locate areas of interest and produce 'maps' to these, as discussed below. The aim was to decrease the time spent on locating suitable inclusions during SIMS analysis and to produce a list of prioritised inclusions and areas within these to ensure that those with the most potential were explored first but also to provide 'back-up' options if these were found to be unsuitable (see below).

Operating on a similar basis to EPMA (Chapter 5) SEM allows rapid imaging of features within a sample, both compositional and topographic[67] at a wide range of magnifications which parameters – crucially – can be rapidly readjusted. Semi-quantitative EDX analyses were also conducted (using the same machine) at all areas flagged up for possible SIMS investigation[68]. The combination of compositional and image-based information allowed not only the determination of suitable inclusions for further investigation, but also the detailed mapping of their location so that ToF-SIMS work could proceed rapidly: although the ToF-SIMS equipment is capable of highly detailed localised imaging, it takes much more time to build up these images, and it does not possess the same broad range of magnifications available with SEM.

The series of images presented in Figure 6.7 provide an example of the way that information was gathered with SEM prior to ToF-SIMS analysis, in this case for sample Th153. After an initial examination four areas of interest deemed suitable for ToF-SIMS analysis were highlighted (image [1]). The areas were then prioritised (in this case in the order D; A; C; B) and investigated separately, so that maps could be followed to the next should the first be found unsuitable. In this example, area D was found to be suitable. An example of the 'maps' of various magnification is shown in image [2]. SEM images were taken in both back-scattered and secondary electron modes, so that any possible confusion between topographic and compositional features could be resolved. Care was taken to highlight the limits on each image on its lower magnification counterpart so that features seen at higher magnification could be placed within their broader context: this is important as those features which appear clearly defined under SEM imaging modes may not appear in the optical imaging mode under ToF-SIMS. Semi-quantitative EDX results were also taken for each area of interest, as shown in the inset to image [3].

It should be stressed that a large number of possibly suitable inclusions were identified. This was necessary due to the different depths of analysis of SEM and ToF-SIMS: inclusions or other features below the sample surface can appear on SEM (SE and BSE)

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[67] In the present study, which used polished samples, the topographic features include holes deriving from air bubbles within the glass and – for the Greek samples – some surface inconsistencies resulting from weathering. It should also be noted that back-scattered (compositional) and secondary (topographic) electron modes both give a little information on composition *and* topography so that by using them in combination it is possible to compare the images thus acquired.

[68] As noted in Chapter 2, some of the samples analysed by ToF-SIMS have previously been examined using quantitative EPMA. The aim of SEM (EDX) point analyses, therefore, was primarily to determine any local compositional anomalies in those areas selected for possible ToF-SIMS analysis: the quantitative, bulk composition of the samples was already available. It was also necessary to avoid analysis of the same areas as those investigated with EPMA, in order to minimise the changes effected by electron microscopy on the samples themselves, most notably the increased mobility of alkalis under the electron beam.

images, but will not be detectable by the limited depth of analysis of ToF-SIMS. It is recommended that future investigations adopt the same detailed processes to maximise the use of time on the ToF-SIMS equipment itself and to ensure that the most promising inclusions are identified and investigated.

An optical camera attachment allowed the location of individual samples within the stage during ToF-SIMS analysis. Some features identified by SEM, including holes and larger inclusions as well as the sample edges, could be seen with the optical equipment. Pre-identified areas of interest could then be found within each sample using total secondary ion imaging and distance measurements from strong / clear features such as the sample edge.

The above means of investigation allowed the most suitable inclusions to be found, analysed and imaged with ToF-SIMS, something which was not possible in the previous (pilot) study due to the more limited preparation, and the subsequent difficulties in locating areas of interest within the allowed time-frame.

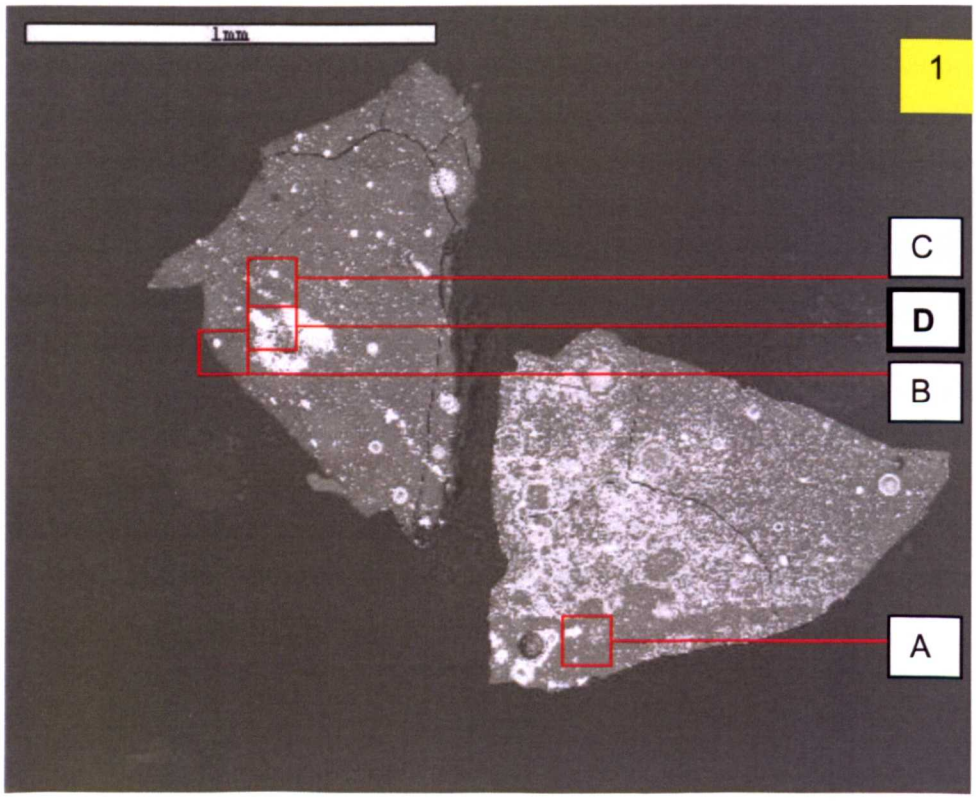

Figure 6.7 (continued on next page)

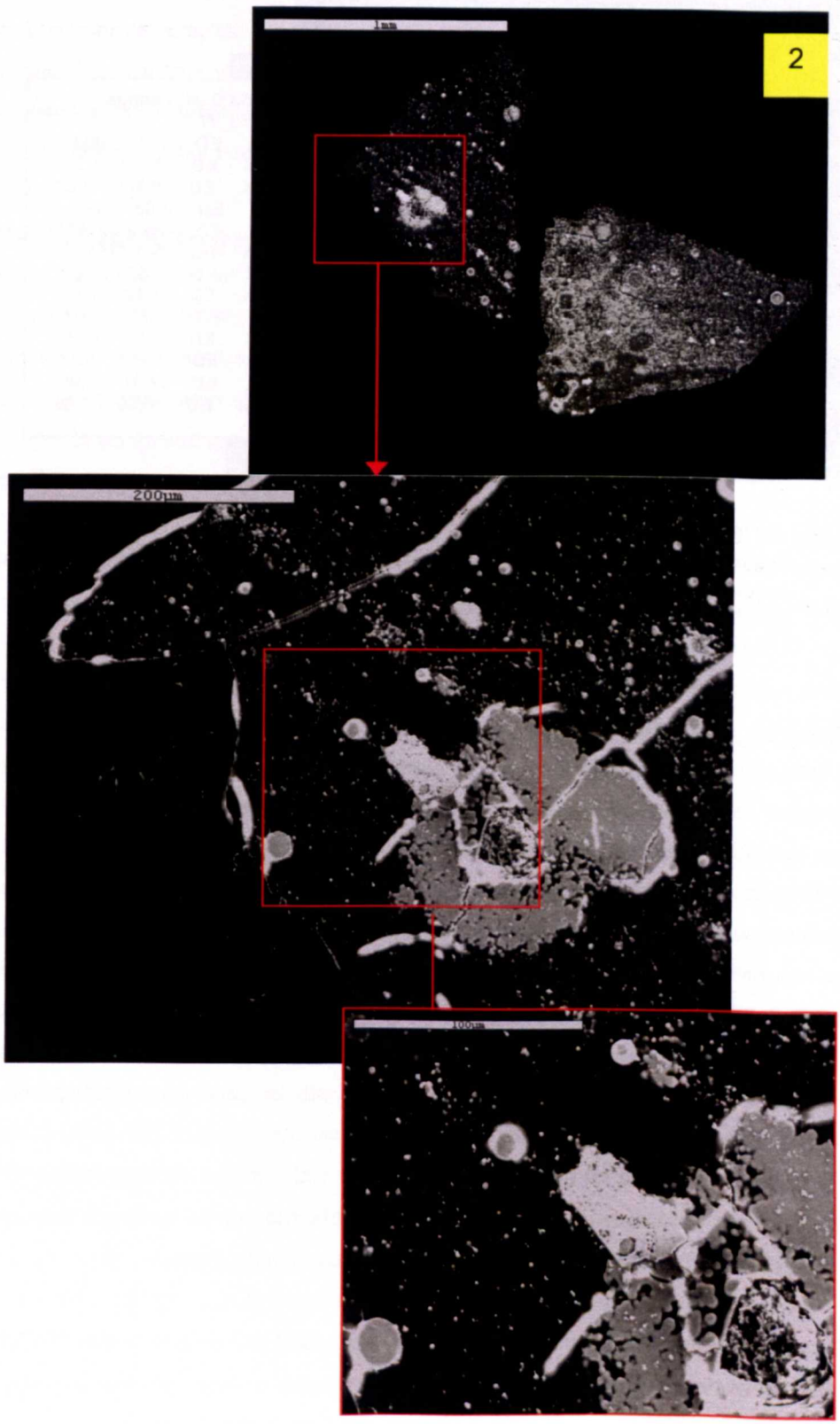

Figure 6.7 (continued on next page)

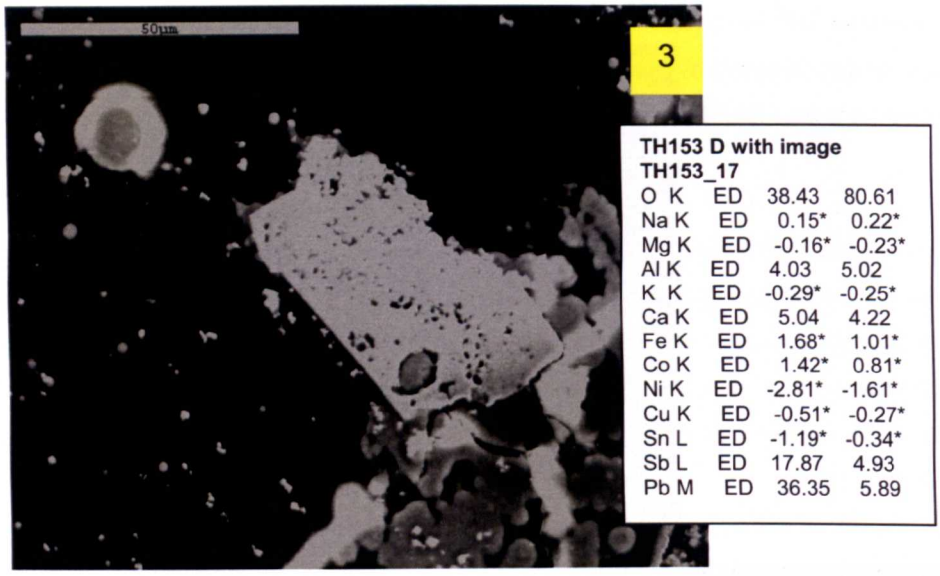

Figure 6.7 ToF-SIMS Preparation Using SEM.
Information gathering using SEM to locate suitable inclusions, create maps to them for use with ToF-SIMS, and identify their basic chemical signature.
Given in stages **[1]**, **[2]** and **[3]** (labelled in yellow, top right of images).

A Note on Sample Prioritising[69]

A total of fourteen samples of calcium- and lead-antimonate opacified glass were mounted, prepared and analysed / mapped using SEM. The time constraints of usage on the ToF-SIMS instrument meant that only four samples could be satisfactorily investigated. This was partially due to the need to re-optimise operational parameters as the SIMS instrument was upgraded since the pilot study and the 2007 test run, when a gallium ion source was used. It was decided that a larger number of samples should be prepared, however, in order to provide as many 'back-up' options as possible in case of difficulties in locating inclusions, etc. Indeed, investigation found that the corrosion in one of the three Greek samples was so severe that despite polishing during sample preparation the surfaces were uneven, interfering with the analytical capabilities of ToF-SIMS (which is very sensitive to sample topography). The same was also true of one sample from Tell Brak and one from Amarna. Those samples which could not be analysed, but were deemed suitable, will be prioritised for ToF-SIMS analysis in the future.

Once the samples had been initially investigated with SEM and their suitability for ToF-SIMS briefly examined within the instrument itself, it was possible to select those samples to be used for full investigation. It had been decided to investigate two samples of calcium-antimonate opacified glass and two of lead-antimonate opacified glass. It was also attempted to provide some distinction between regions, so that one sample from Amarna (opaque yellow) and one from Tell Brak (opaque light blue / turquoise) were

[69] For a discussion of sampling strategy, the reader is referred back to Chapter 2.

analysed, along with two from Mycenaean Thebes (opaque white and opaque yellow). No lead antimonate samples from Tell Brak were available, and the calcium antimonate sample from Amarna was found to be unsuitable for analysis due to holes, so that a comparison between the use of the same antimonate opacified glasses between regions was, unfortunately, not possible.

ToF-SIMS Investigation

Since the pilot study of the use of ToF-SIMS in the investigation of ancient glass (summarised in Rutten et al. 2009) the ION-TOF analyser used has been upgraded and its primary ion source has been changed from a (monotonic) Ga to a Bi cluster source. The experimental parameters thus had to be re-established in order to take into account the changes in equipment as well as optimising the collection of signals (see below) and are thus described in some detail here.

Once a suitable area of interest had been located, it was locally sputter cleaned to remove hydrocarbon contamination from the surface. This is necessary due to the extremely limited sampling depth of ToF-SIMS (~1-2nm) and the consequent interference of any surface contamination with the spectra obtained, as mentioned above. For the pilot study this cleaning procedure was performed by briefly exposing the sample to an intense primary ion beam and the same procedure was followed here, using Bi_3^+ primary ions. Where an inclusion was returned to later and a second cleaning was required, Bi^+ ions were used in order to minimise the amount of sample material removed along with any returning contaminants. It was also found, however, that leaking a small amount of O into the vacuum chamber during exposure to the primary ion beam removed low intensity, higher mass hydrocarbon peaks from the resultant spectra. Cleaning was performed by first leaking the oxygen and then randomly rastering the primary ion beam over a 300 x 300 μm area surrounding the inclusion of interest. The use of a random raster prevented potential charging due to the intense ion beam used for the cleaning process.

A combination of Bi^+ and Bi_3^+ primary ions was employed for the acquisition of both spectra and images. Testing of both Bi^+ and Bi_3^+ primary ions (in negative and positive modes) on the first sample to be analysed in this study demonstrated that the Bi_3^+ ions were more suited to the identification of compounds or the heaviest elements while Bi^+ is generally preferential for the identification of individual elements. Pulsed low-energy electrons (20eV) were used to negate any charging effects due to the primary ion beam without affecting the surface chemistry.

Each area of interest was analysed in terms of both positive and negative ions. The positive ion spectrum provides more detailed general information for the majority of elements and compounds, but for some the negative ion spectrum is more suitable: for

example, it was found that the negative ion signal provides higher resolution data on antimony and bismuth, both important signifiers in the composition of ancient glass, as discussed below. Past research into antimony compounds using ToF-SIMS has suggested that oxidation state has a strong influence on the yield, and it has been illustrated that negative ion spectra are generally more sensitive to oxides (see Briggs 2001, 467): this was also found to be the case with antimony oxides in the samples of archaeological glass analysed by Rutten et al. (2009, 975).

It was also necessary to run separate analyses for mass-specific and spatial data. For the former, the high current bunched (HCB) beam mode, providing high mass resolution was used. As this does not provide the optimum spatial resolution, however, image data and their associated spectra were also gathered using burst alignment (BA) mode, providing high spatial resolution. Spectral and spatial information was acquired for both positive and negative primary ion beams. Spatial data gathered from high mass resolution mode and saved as a raw data stream (RDS) was also available during post-analysis, and was used in order to generate spectra from isolated areas within the window analysed (used for direct comparison of the composition of matrix and inclusions, discussed below). Thus each area required a minimum of four sets of scans. For each image and its associated spectra, 50 scans were taken using random rastering of a finely focused beam across the area of interest, producing mass resolved secondary ion images.

Post-Analysis

After the primary analysis it was necessary to perform a number of operations using the IonSpec and IonImage (both version 4.0, ION-TOF GmbH of Münster, Germany) programmes associated with the ION-TOF mass analyser, in order to resolve the information gathered and render it suitable for interpretation.

As noted, spectra are recorded in both high mass and high spatial resolution mode during the primary ToF-SIMS analysis. For both modes the area scanned is saved as a number of separate spectra, each of which corresponds to one pixel in the image as illustrated in Figure 6.3 (above). Fifty scans were made per pixel, so each spectrum is the result of 50 separate incidences of data acquisition through the mass analyser. Because the data is saved as a RDS it can be returned to at any time in order to reconstruct the spectra for any pixel or selection of pixels within the area originally scanned.

Calibration

Mass calibration was performed using the IonSpec programme, as illustrated in Figure 6.8. The raw data file is visually displayed as a series of peaks with time on the x-axis. Some of these peaks are distinct and easily identified due to their known mass and typical peak pattern. A selection of such characteristic peaks is used for calibration. Lower mass and

organic species were found to be particularly useful for identification. Once these peaks had been manually labelled, a wider range of peaks was selected and their identification tested by comparison to the labelled peaks: where deviation (in parts per million) is found to be less than +/-50 and where the 'fit' is better than 90% (Frank Rutten, personal communication) for a number of easily identifiable peaks the whole spectrum can then be calibrated. 'Fit' is calculated by the software and describes the amount of the peak intensity (in %) that can be explained by the proposed substance, taking into account expected isotope intensities. For the positive spectra, H, Li and CH_3 were particularly useful for this exercise. For the negative, O, OH species and F were suitable. High mass resolution spectra were calibrated first and high spatial resolution data was adjusted using this information, in the process described below. As the species of interest were inorganic, peaks used for final calibration were also selected from such species (such as Na). This ensured the optimal identification of the inorganic-related peaks of interest.

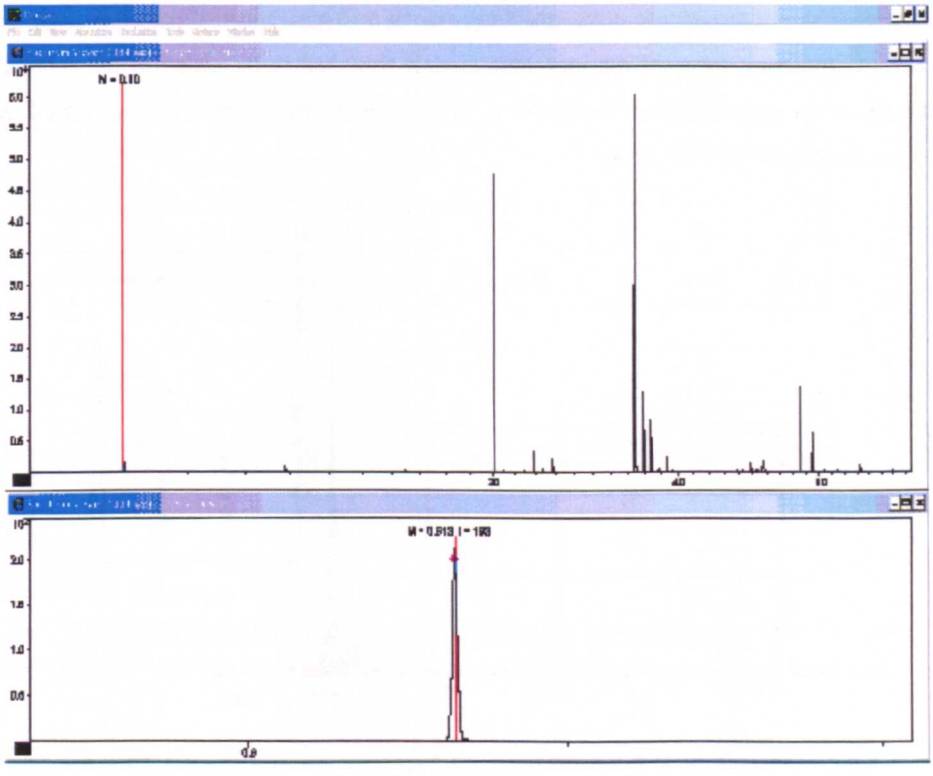

Figure 6.8 Identification of Peaks for Calibration.
The image shown in the top window corresponds with an expanded view in the bottom window, where the outline of a peak (in this case H) may be defined. Image taken from the IonSpec software.

Assignment of Peaks

The assignment of spectral peaks is of vital importance in the process of analysis. Following calibration, specialised peak lists are drawn up for both positive and negative ions. Identified peaks are used as the basis for image formation based on the nominated spectra, but they also allow comparison between samples as a single peak list can be used to compare between multiple spectra. The latter property also means that a peak list can be

refined and checked against a large amount of data before the assignment of certain peaks is accepted.

The downside of the strength of ToF-SIMS in detecting all elements is that interference between peaks of similar mass is often encountered. Given the time-consuming nature of the process, it is thus necessary to begin by selecting those peaks which are known to be present in the sample (based on EPMA or SEM results and an examination of the literature), by referring to the distribution of unknown species in the images, and by examination of the spectra for ROIs and unexpected peaks of interest. It was thus necessary to identify the peaks of interest manually. This was initially approached in two ways: either by instructing the software to identify the peak(s) for a particular element, isotope or compound; or by selecting certain peaks and identifying them from a list of possibilities relying upon absolute mass and isotope distribution. Either method requires further checking, however, not least because those lists present within the software are constructed from assignments made during previous analyses, most of which were based on organic material: some of the inorganic signals thus had to be added to the software manually in the course of peak assignation. The processes by which this was carried out are now described.

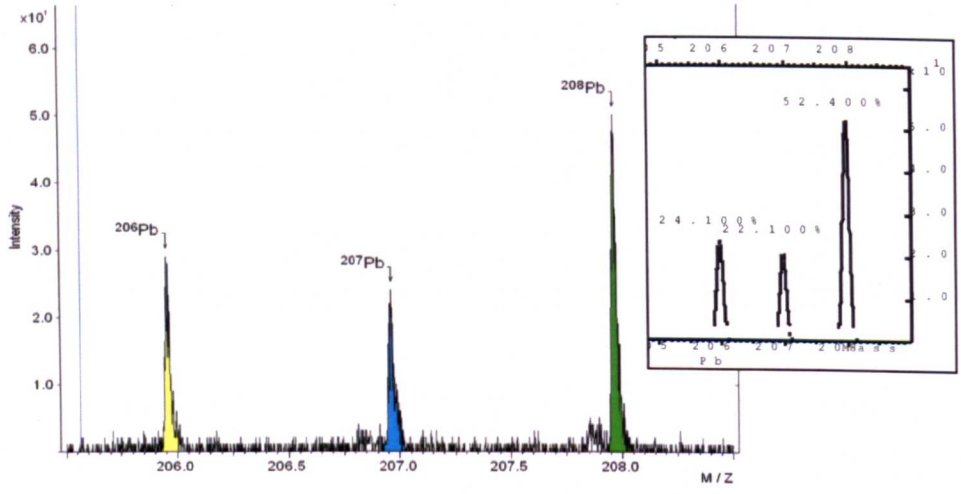

Figure 6.9 Confirmation of Peak Assignment Using an Isotope Cluster Chart.
Lead isotopes in Am2 (top) compared to relative lead isotope cluster chart (inset) for the three most abundant isotopes of lead.
Cluster chart accessed within the IonSpec software.

For the high mass resolution data, there are a number of methods by which peak identification can be tested against possible interference from other species at similar mass. In several cases, the assignment of peaks at a particular mass could be confirmed by examination of the expected pattern of isotopes for a particular element or compound. Isotope cluster diagrams (available within the IonSpec software) were used in order to confirm the expected spread of peaks. Figure 6.9 illustrates this process for the assignation of peaks representing isotopes of Pb: the relative intensity of the signals at mass 204 (not

shown), 206, 207 and 208 were found to concur with the relative natural abundance of the isotopes of Pb and did not show evidence of interference from other peaks. Furthermore, where the main isotope of a particular element or oxide is found to overlap with another signal, the weaker isotope(s) allow confirmation of the signal and its relative intensity of distribution within the images. For compounds, it was often found to be useful to search for the presence of their constituent elements within the spectrum before confirming their assignation.

Occurrence of a number of peaks resulting from fragmentation of the same compound in the SIMS experiment was also taken into account in order to test the strength of assignations, in particular of compounds. An example is illustrated in Figure 6.10: for silica, expected signals include those which would have been fragmented (under the sputtering process) from the silicate tetrahedra of which the glass network is formed, resulting in signals from SiO, SiO_2 and SiO_3, as well as elemental Si and O. The presence and identical spatial distribution of all of these signals strengthened the assignation of each.

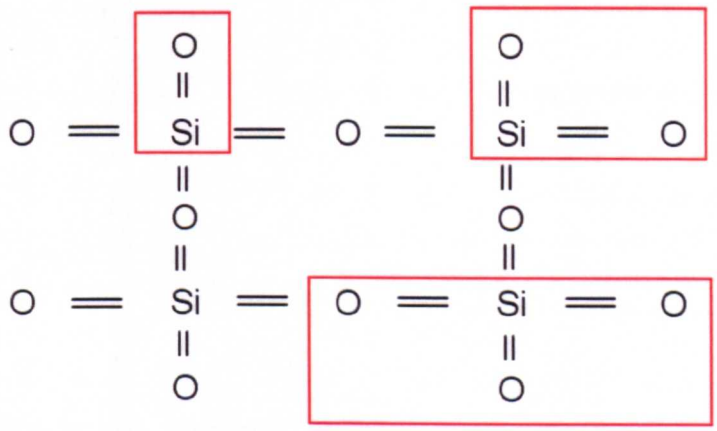

Figure 6.10 Schematic Example of the Importance of Considering Stoichiometry in Assigning Peak Labels.

Once created, positive and negative peak lists were tested between, refined, and applied to high mass resolution spectra from the four different samples analysed. It was then necessary to identify the far less clearly defined peaks of the high spatial resolution spectra: each high spatial resolution spectrum was examined with reference to the corresponding high mass resolution spectrum. This was necessary because the high spatial resolution data provides far less clearly defined peaks. An example is shown in Figure 6.11: here, the high mass resolution peak (left) for Na was found to correspond clearly with the high spatial resolution peak (right), despite the increased width of the latter. The high mass resolution spectrum reveals that Na is isolated: that is, no other peaks are present in the surrounding area which is encompassed by the corresponding peak in high

spatial resolution mode. In this case the identification of the high spatial resolution peak as corresponding to Na was confirmed.

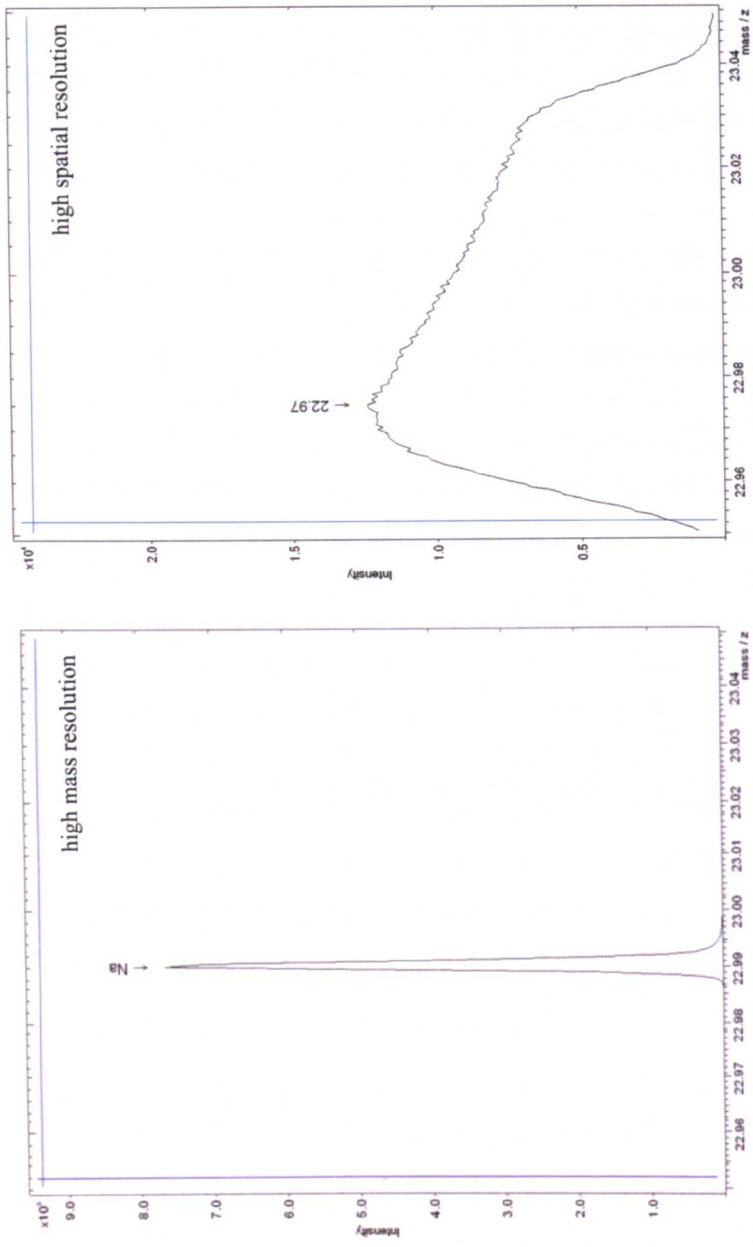

Figure 6.11 High Mass and High Spatial Resolution Peaks Compared.
Note that a different scale has been used in the Y axis: the difference in intensity between the peaks generated by the two modes is too great to show a comparative scale.
From sample Am2, positive ion results.

In some instances, however, the confident identification of peaks was not possible. Figure 6.12 illustrates two problems which were encountered in the identification of peaks, both based on interference between signals of a similar mass. The image on the left shows an instance of interference between two peaks in high mass resolution mode: peaks 1 and 2

could be separately identified in the spectrum but interfere with one another in imaging mode.

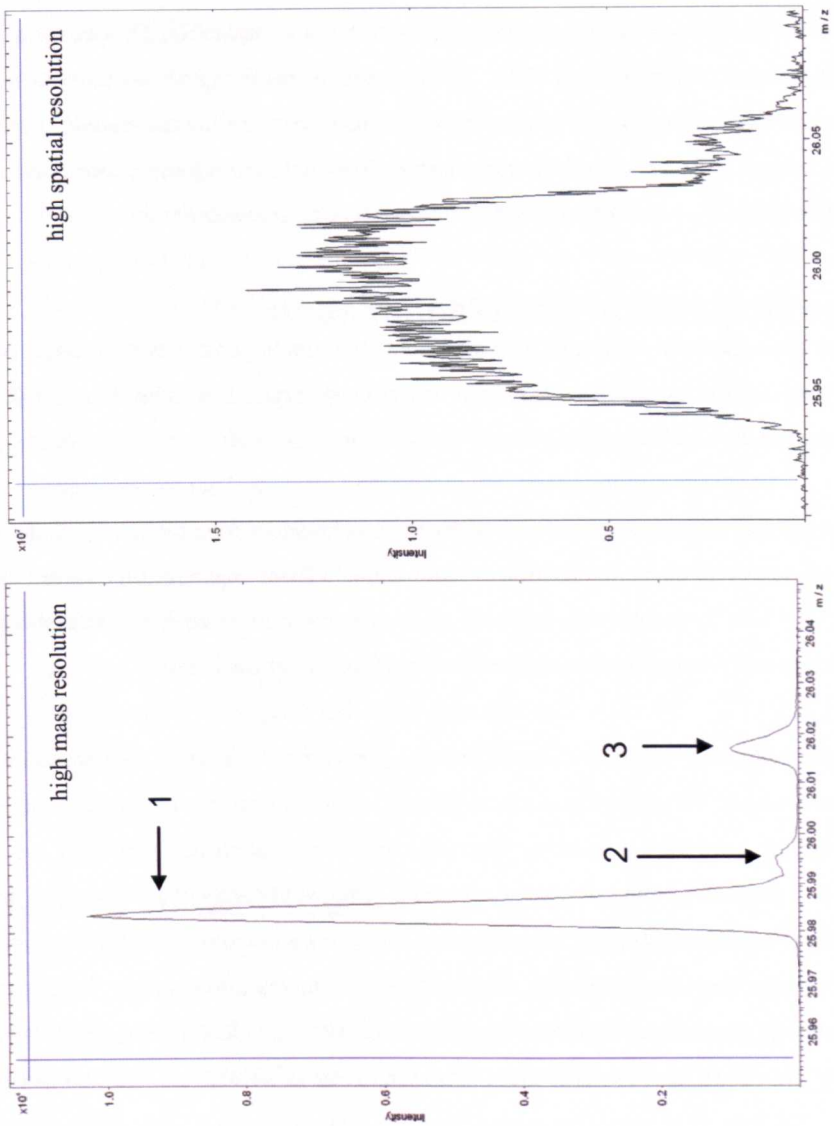

Figure 6.12 Interference between Peaks in High Mass and High Spatial Resolution Modes.

Different scales are shown for the X and Y axes of the two images due to a large difference in height and width of the peaks.
From sample Am2, positive ion results.

Where one peak is significantly larger than another, as in this example, the interference was minimal and a useful image could still be produced, provided that this was noted. Similarly, where two peaks from associated species (such as ^{29}Si and SiH) were found to interfere with one another, the images produced could still be of use, again provided that the interference was noted. The situation becomes more complicated where high spatial resolution data is considered, however, as the width of the peaks produced means that a number of signals can become incorporated into a single peak, and will thus be inextricably associated in the images produced. The image on the right illustrates the

incorporation of peaks 1 – 3 (identified in high mass resolution mode) into a single, broad peak in the high spatial resolution spectrum. In such cases, it was necessary to examine carefully the images produced by high mass resolution data in order to ascertain whether those produced by high spatial resolution spectra were comparable. On occasion it was found that isolated signals from ROIs were helpful in resolving these issues where the interference came from signals originating from different areas of the sample. Reference between images and spectra of high mass and high spatial resolution, and for positive and negative ion signals, was thus necessary at every stage of analysis.

Image Acquisition and Manipulation

Once the data has been calibrated and a number of suitable peak lists have been built up and tested, it was possible to produce images correspondent with both high mass resolution and high spatial resolution spectra, and for both positive and negative ion data.

Because the transition from detection of positive to negative ions requires a re-setting of the experimental parameters, the images reconstructed from negative ion data are slightly (spatially) off-set by comparison for those reconstructed from positive ion data, though the primary areas of interest have been identified in all resultant images.

Various techniques of manipulation are possible for either positive or negative ion images of a given sample. Of particular use here was the summing option, by which a number of signals can be combined in order to produce a higher resolution image (higher resolution due to the increased number of counts per pixel). This was primarily used where a number of signals related to a particular element (such as oxides and isotopes of Si) were found to originate from the same region(s) of the sample. Images showing the heterogeneous distribution of up to three different signals (which can include summed data) were also produced, though these were used more for the purposes of illustration than interpretation.

The image labels are based on the assignation of calibrated peak lists, as described above. The IonImage software recognises labelled peaks and uses these to reconstruct the image from the RDS. Unassigned peaks were also included in the first stage, in order to determine whether they revealed any significant compositional heterogeneity and thus required assignation or consideration.

ROIs were selected using the high mass resolution images with reference to the high spatial resolution images to ensure no finer details were omitted (for example, the presence of a small area of different composition within an inclusion). For each sample, the inclusion itself and a relatively homogeneous area of the matrix were isolated as ROIs. A spectrum from each ROI was then obtained, allowing high definition comparison between the specific composition of the matrix and that of the inclusion.

Stages of Post-Analysis

In reality, it was necessary to return several times to the stages outlined above, in order to refine the detailed interpretation based on the full range of data. The process followed (from the initial analysis to generation of final images) can be summarised:

1. Samples are first analysed by quantitative EPMA and / or SEM.
2. High mass resolution spectroscopy is conducted, retaining raw data which allows the subsequent generation of low spatial resolution images.
3. High spatial resolution imaging is conducted, retaining raw data which allows the generation of spectra from specific areas which can be compared with (2).
4. The high mass resolution spectra (2) are examined for expected signals (1) or those pertinent to issues raised in the literature. The assignation of labels to peaks is confirmed by recourse to peak lists, stoichiometry and expected composition.
5. High spatial resolution images are generated using peak lists produced by comparison of the high mass and high spatial resolution spectra.
6. Regions of interest are isolated. Spectra from these allow the comparison of inclusions with the matrix or comparisons between specific areas (matrices, inclusions) of separate samples.
7. Anything unusual or unexpected in the spectrum or the images is examined and – where possible – assigned and added to peak list.
8. Images are generated using the new peak lists (7). Stages (6) to (8) are repeated as necessary.

Summary of Methodology

The methods presented above were found to be essential for the comprehensive and detailed characterisation of inclusions in opaque glass, and the results are presented in the following section. A large part of the present study has involved defining experimental procedures for the examination of archaeological glass using ToF-SIMS. It is hoped that the current work will provide a clear outline for future research in this area and in particular will minimise the time spent on locating samples and optimising the equipment (for example, deciding which ion source is most suitable for particular signals as discussed above). Once these issues had been dealt with, it was possible to locate and fully analyse a single inclusion in one to two hours. Post-analysis takes much longer, but in this case the period of time spent is largely dependent on the level of information required to address the questions being asked of the data. In addition, the raw data can be returned to and re-analysed with the dedicated software as many times as necessary. It is suggested that future research, where possible, uses the methods and procedures outlined above.

6.c. Results and Discussion

The results of ToF-SIMS are presented below. The samples are first considered in turn, grouped into those coloured and opacified with calcium and lead antimonate respectively, and discussed with reference to images and spectra associated with the location of major and minor elements. The latter were taken as a starting point in the investigation as they were known to be present based on SEM (EDX) examination of the specific areas selected for investigation with ToF-SIMS. A number of primary peak lists (positive and negative ion spectra; high mass and high spatial resolution) showing only those signals which could be unequivocally identified were used initially for all samples, facilitating comparison of spectra and images between the four samples.

Following this is a more detailed discussion of secondary ions with particular relevance to the detection of selected trace and minor elements, and a consideration of the implications of these results in an attempt to define the possible sources (and pre-treatment) of opacifiers. The discussion then readdresses the issues with reference to all four samples and to the broader archaeological context of the results. Finally, suggestions for the optimisation of the use of ToF-SIMS in studying ancient glass are presented, with a consideration of the avenues for future work. Full details of the four samples discussed below, including references to relevant publications, can be found in Appendix 1.

Calcium Antimonate Opacified Samples

The two samples Th267 and Brak12 were shown by SEM and EPMA respectively to have been coloured and opacified by calcium antimonate. Semi-quantitative SEM analysis illustrated that Th267 also contained impurities including Pb and Sn. The published EPMA results for Brak12 are reproduced in Table 6.1. In addition to these, SEM revealed the presence of Sn in this sample (this is discussed below).

	Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	Cl	K_2O	CaO	TiO_2	Cr_2O_3
wt. %	16.1	7.6	1.9	62.4	0.1	0.4	0.6	3.7	6.1	nd*	nd

	MnO	Fe_2O_3	CoO	NiO	CuO	ZnO	As_2O_3	SnO_2	Sb_2O_3	BaO	PbO
wt. %	0.1	0.3	nd	nd	1	nd	0.2	nd	5.5	nd	nd

*nd = none detected

Table 6.1 Quantitative EPMA results for Brak 12.
Published in Henderson (1997, 96).

Figures 6.13 and 6.14 summarise the key positive and negative ion results respectively for the distribution of the major and minor elements, isotopes and oxides which could be confidently assigned in Th267 (as discussed in the methodology). The inclusion examined was found to be a feathery, dispersed agglomeration of Ca and Sb, which were more

concentrated towards what appears to be the centre of crystal growth. Mg, Si, Na and K were elevated in the matrix. Elemental Al was found across the area analysed but was elevated in the matrix. AlO_2, however, appeared to produce a stronger signal from within the area of the inclusion. Given the higher signal for O from within the inclusions, however, also visible in Figure 6.14, it is possible that this reflects the difference in the surrounding chemistry of the Al rather than a distributional difference, as almost all elements within glass are present as oxides (see Chapter 3).

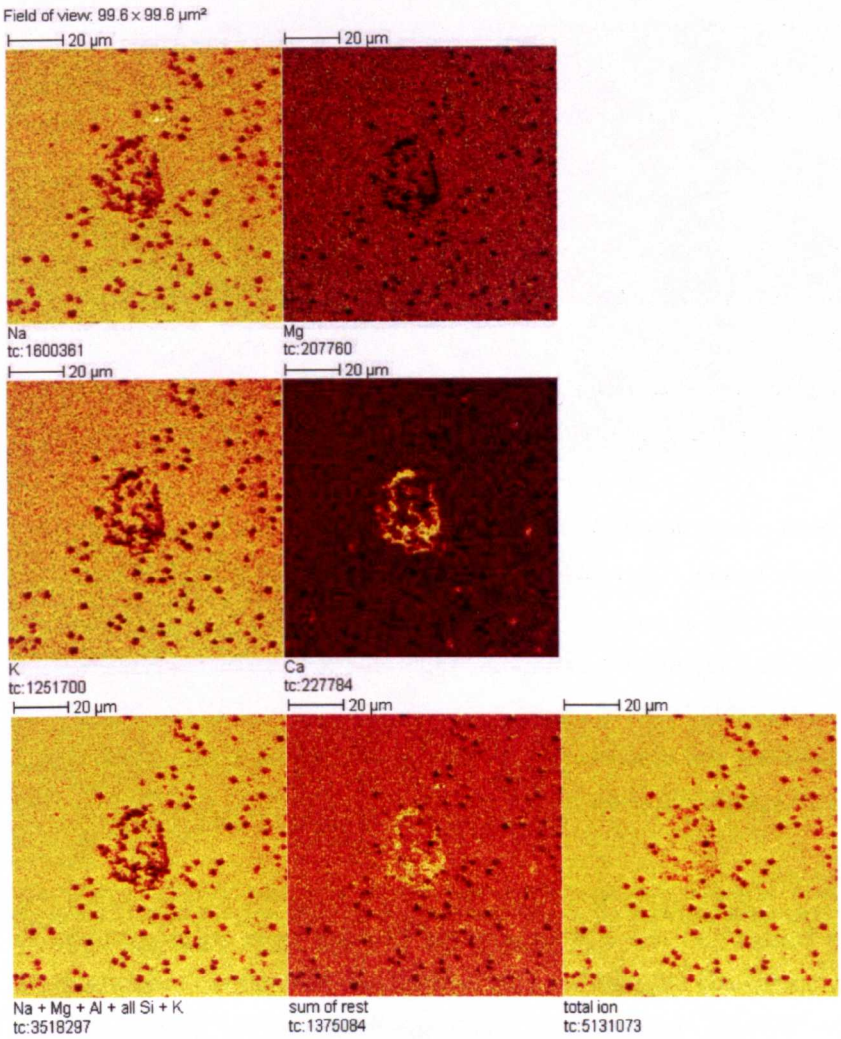

Figure 6.13 Positive Ion Results for Selected Major and Minor Elements in Th267. The total counts (tc) for each signal appear at the bottom left of its image. The field of view (99.6 x 99.6µm^2, given in the top left) is the same for all following images. 'Sum of rest' describes those signals not labelled here: these include H and O species and those signals which could not be resolved. The total ion image (bottom right) shows the total signal retrieved: in this case the matrix produced slightly stronger signals than the inclusion.

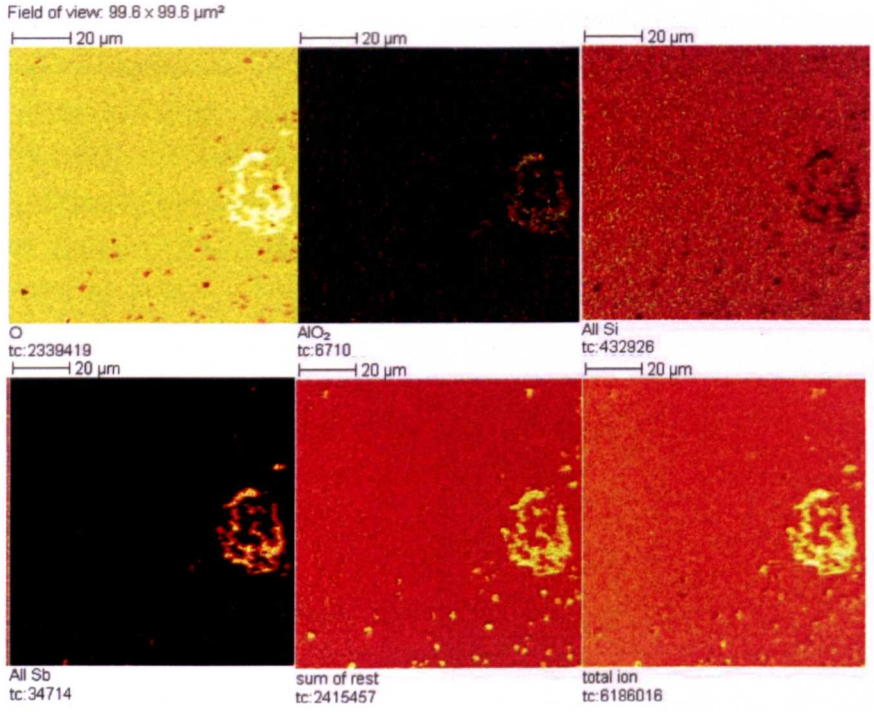

Figure 6.14 Negative Ion Results for Selected Major and Minor Elements in Th267.
'All Si' is a summed image for Si, ^{29}Si, SiO_2 and SiO_3.
'All Sb' is a summed image for SbO_2 and $^{123}SbO_2$.

It is apparent that a number of smaller features are also present within the matrix of Th267 (concentrated to the bottom right of the images presented). Several of these were found to produce the same signals as the large inclusion, most clearly visible in the positive ion image for Ca (Figure 6.13) and the summed image for Sb ('All Sb', Figure 6.14). Several others, however, appear to be holes, probably formed by the removal of inclusions during grinding and polishing and contaminated by other species during sample handling and transference to the vacuum chamber.

The positive and negative ion results for the opaque turquoise sample Brak12 are summarised in Figures 6.15 and 6.16 respectively, for those major and minor elements which could be confidently assigned. It should be noted that the negative ion area analysed is slightly offset from the positive, though the main features of the inclusion and the surrounding area were still discernible. Both SEM imaging and later ToF-SIMS revealed that this sample did not contain as many well-defined inclusions as the sample of opaque white glass (Th267). The area selected for analysis shows a large, relatively dispersed agglomerate inclusion. Its delicate, feathery form is comparable to that of the inclusion analysed in Th267, described above. As with Th267, the inclusion was found to consist of Ca and Sb and the matrix was enriched in Si, Mg, Na and K. The nuclei of crystal growth, more concentrated in Sb and Ca, can be clearly seen on these images. The distribution of Al and AlO_2 was also comparable to that discussed above though, probably due to the

more dispersed nature of this inclusion, even less preferential distribution could be seen between inclusion and matrix.

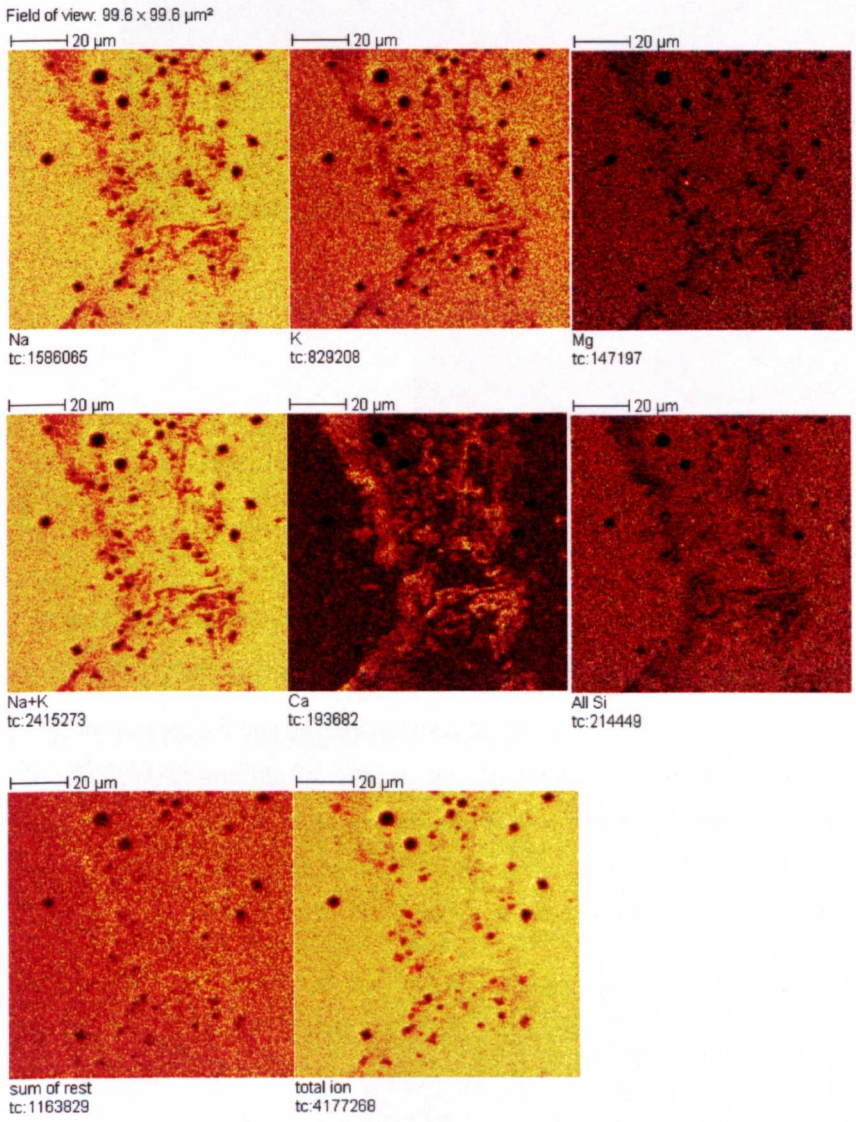

Figure 6.15 Positive Ion Results for Selected Major and Minor Elements in Brak12. 'All Si' is a summed image for Si, ^{29}Si, and ^{30}Si.

Because Sb preferentially forms from a glass melt, the strong concentration of Sb within the inclusions cannot be used to determine (on compositional grounds) whether they have precipitated from the melt or have remained in the form in which they were added. More revealing is the distribution of other elements associated with the matrix and inclusion and the degree of difference between the two compositions.

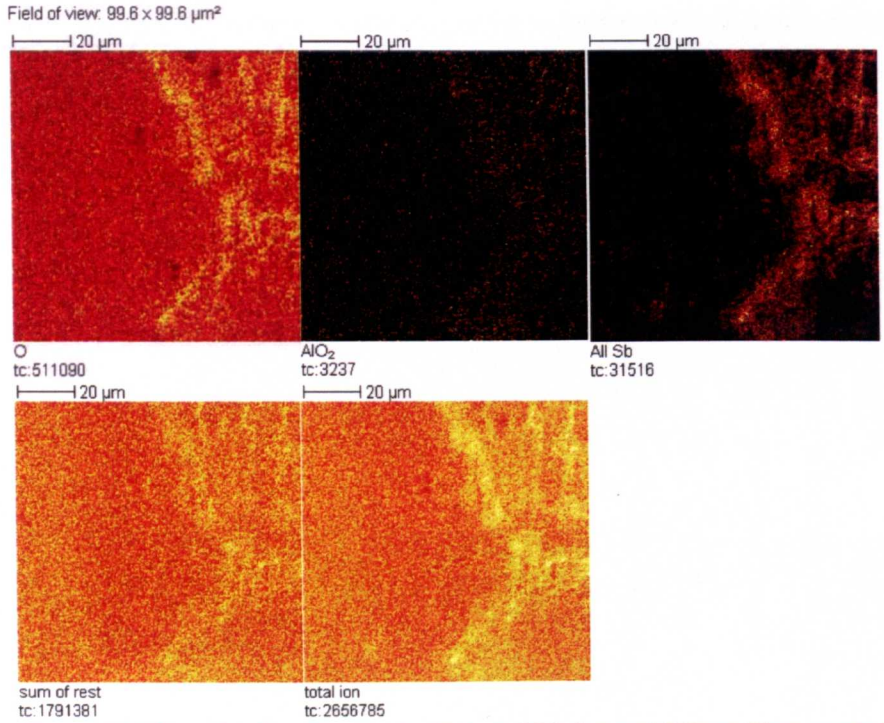

Figure 6.16 Negative Ion Results for Selected Major and Minor Elements in Brak12.
'All Sb' is a summed image for SbO_2 and $^{123}SbO_2$.

ROIs were thus selected for the two calcium antimonate samples and the spectra for these pixels were calibrated in order to establish the degree of difference between the composition of the inclusion and that of the surrounding area in high mass resolution mode. The matrix ROI for Th267 was obtained from the area of the matrix containing no evidence of smaller inclusions, as illustrated in Figure 6.17.

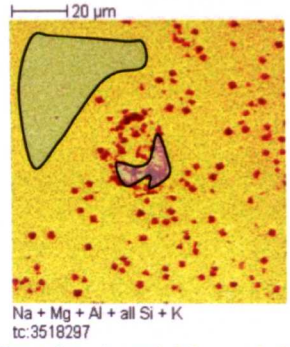

Figure 6.17 ROIs Selected for the Acquisition of Spectra from the Matrix and Inclusion in Th267.
The image shown is the summed image for those signals expected to be associated primarily with the matrix. One ROI was selected from the matrix, and one from the area of the inclusion itself.

As there were also a number of smaller inclusions in the matrix surrounding the larger one in Brak12, and given the size and dispersion of the agglomerate inclusion selected for analysis it was not possible to isolate an inclusion-free ROI within the area shown. A separate portion of the sample was thus analysed in high mass resolution mode, enabling comparison between matrix and inclusions. For the sake of consistency, a smaller ROI

was selected within this separate analysed area in order to correspond roughly to the number of pixels in the matrix ROIs selected from the other samples.

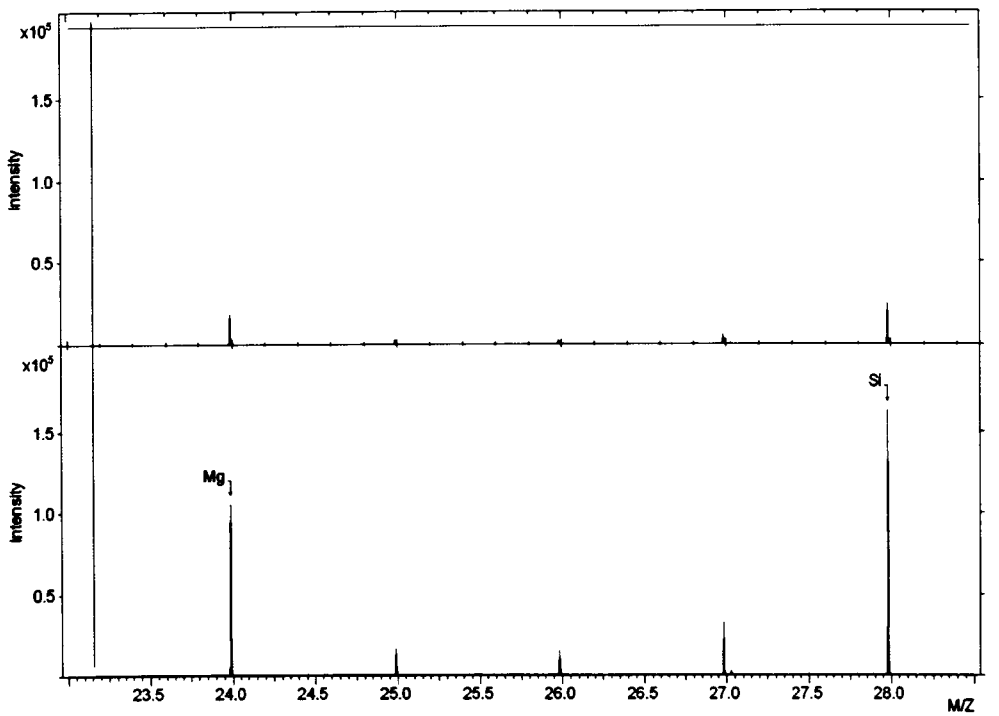

Figure 6.18 Positive Ion High Mass Resolution Spectra Comparing the Inclusion and Matrix in Th267.

For Th267, as illustrated in Figure 6.18, the key elements associated with the matrix (highlighted in a summed image in Figure 6.13, mentioned above) were also present within the inclusion: crucially, in comparable relative proportions. It is possible, however, that the fine morphology of the inclusion is responsible for the presence of matrix elements within the ROI. Figure 6.19 is thus included to illustrate the presence of CaO and Fe in inclusion and matrix. Despite the selection of a smaller ROI for the inclusion than for the matrix, it is apparent that the inclusion contains a higher concentration of CaO and Fe (only the major isotope of which is illustrated), which are also present within the matrix. Again, the key point is the comparable relative proportion of the two in inclusion and matrix. Due to the proximity of the CaO and Fe peaks, it was not possible to isolate and image their distribution in high spatial resolution mode, though the preferential distribution of elemental Ca within the inclusion was imaged (as illustrated in Figure 6.13, presented above). For comparison, Figure 6.20 shows an excerpt from the same section of the matrix for Brak12 as that illustrated for Th267 above. Again, the matrix elements shown were found to be present in the same relative proportions within the inclusion.

The results presented here make it clear that the identifiable stages in manufacturing technology are directly comparable between the two calcium antimonate opacified samples: the ingredients added to both – whatever form they arrived in – were heated until fully molten, and the inclusions precipitated directly from this melt upon cooling. The fine

morphology of the calcium antimonate rich inclusions in both samples is also consistent with their suggested precipitation from the melt, as their 'feathery', delicate forms can only be produced through *in situ* crystallisation (see Chapter 3), and the concentration of Sb and Ca (and their isotopes and oxides) in particular is highest in the centre of the larger inclusions, as can be seen in the images, consistent with outward growth during cooling.

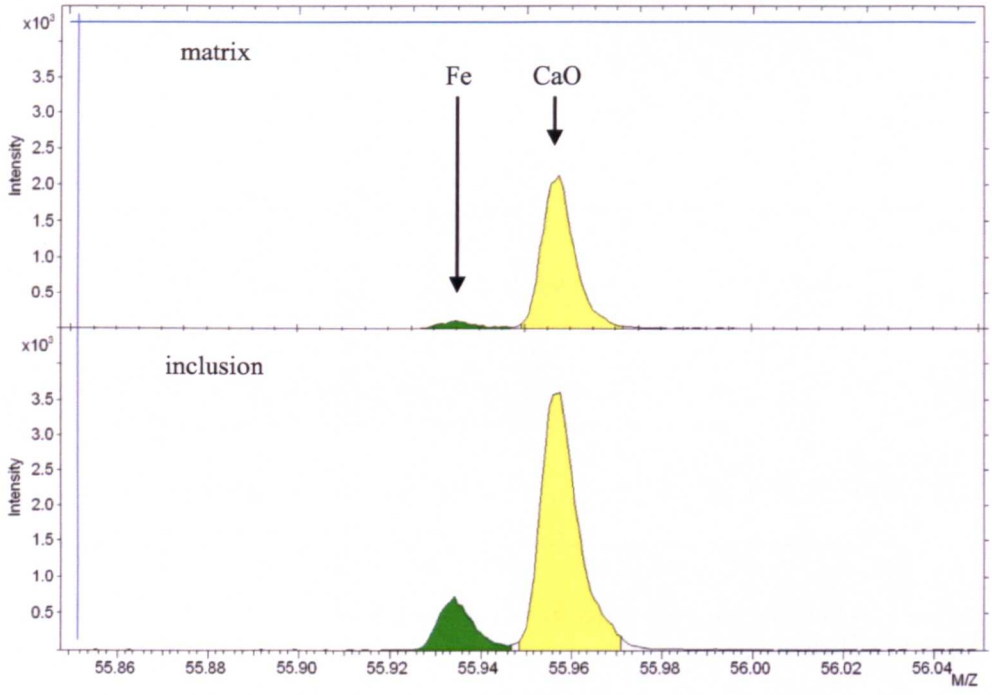

Figure 6.19 Positive Ion High Mass Resolution Spectra Showing Fe and CaO in the Inclusion and Matrix of Th267.

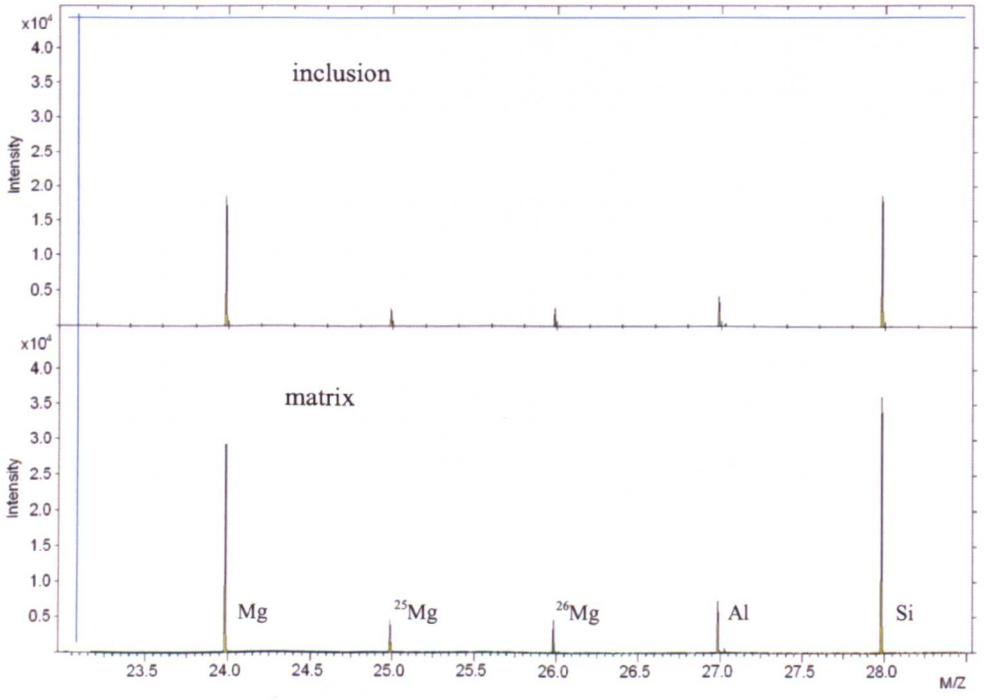

Figure 6.20 Positive Ion High Mass Resolution Spectra Showing Inclusion and Matrix in Brak12.

Lead Antimonate Opacified Samples

The two samples of yellow opaque glass were found to be coloured and opacified by lead antimonate. Semi quantitative SEM analysis illustrated that Th153 also contained impurities including Fe, Cu and Co oxides. The quantitative EPMA results for Am2 can be found in Appendix 2 (sample code 32.408I). In general, it can be noted that the two lead antimonate opacified samples reveal a far greater degree of compositional heterogeneity than those opacified by calcium antimonate, both within the selected inclusions and in the area immediately surrounding them.

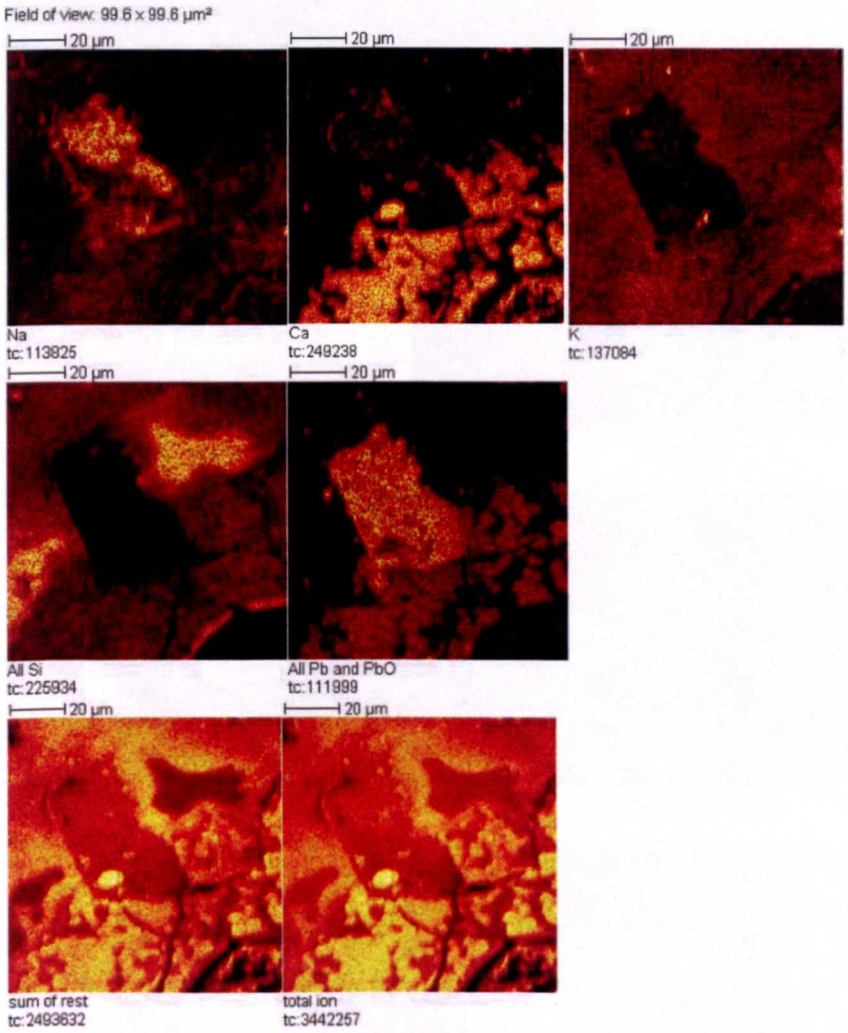

Figure 6.21 Positive Ion Results for Selected Major and Minor Elements in Th153.
'All Si' is a summed image for Si, ^{29}Si, and ^{30}Si.
'All Pb and PbO' is a summed image for ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{206}PbO, ^{207}PbO and ^{208}PbO.

Figures 6.21 and 6.22 illustrate the positive and negative ion results respectively for major and minor elements in Th153. The data discussed below are also summarised in overlay images in Figure 6.23. The analysed area surrounded a large (c.25x40µm), regular, straight-sided inclusion with clearly defined edges, corresponding with the appearance of crystal faces. Some of the edges, however, appear to have been partially dissolved into the

surrounding matrix. The inclusion itself was found to be enriched in Pb and Sb. It was depleted in those elements usually associated with the matrix (Si, Na, K, Ca). It also contains significant concentrations of BiO and BiO_2, discussed separately below. Na, K and Ca, however, were present in certain areas within the inclusion. The presence of elements associated with the matrix within the inclusion may be taken to suggest its precipitation from the former. There is no indication of zoned growth around a nucleus, however, as might be expected if the opacifiers had precipitated directly and completely from the melt (Th267 and Brak12, on the other hand, display a concentration of Ca and Sb in the centre of the inclusions, as discussed above): the irregular location of these matrix elements does not appear to correspond to phases of growth.

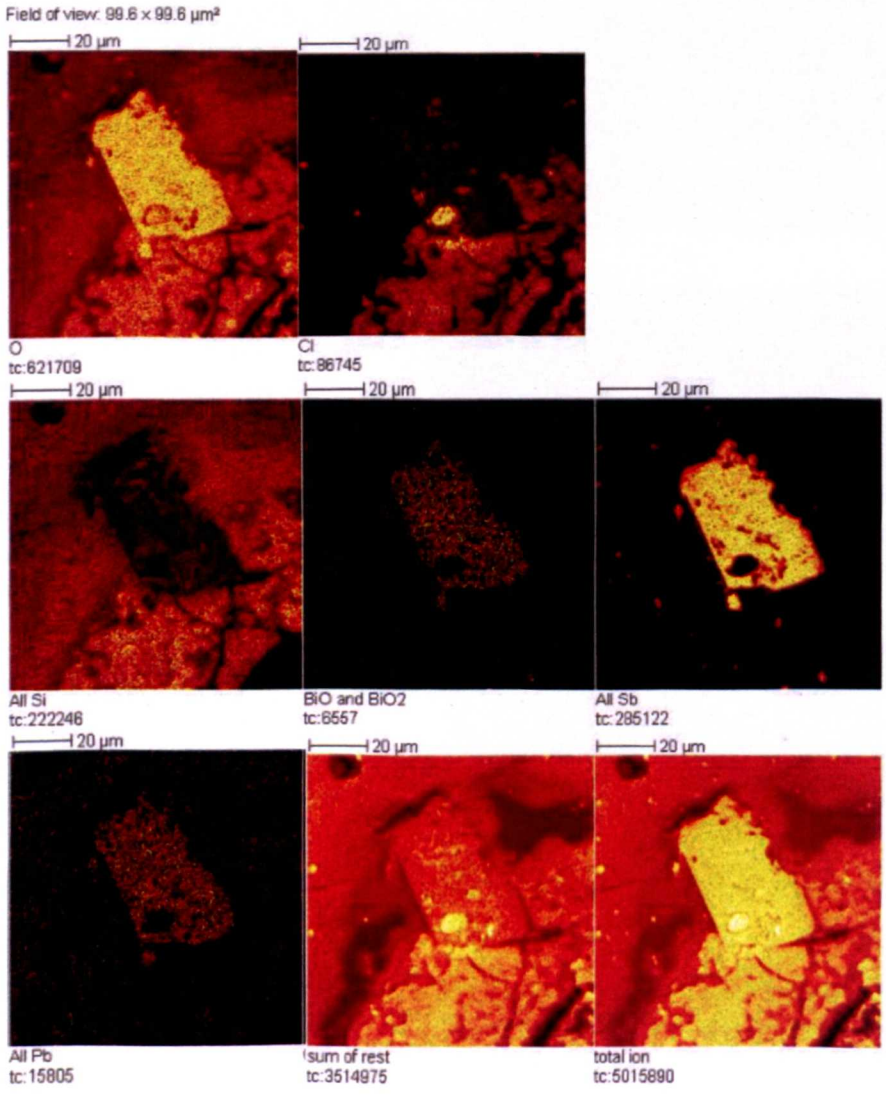

Figure 6.22 Negative Ion Results for Selected Major and Minor Elements in Th153.
'All Si' is a summed image for Si, ^{29}Si, SiO_2 and SiO_3.
'All Sb' is a summed image for SbO^2 and $^{123}SbO^2$.
'All Pb' is a summed image for ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{206}PbO, ^{207}PbO and ^{208}PbO.

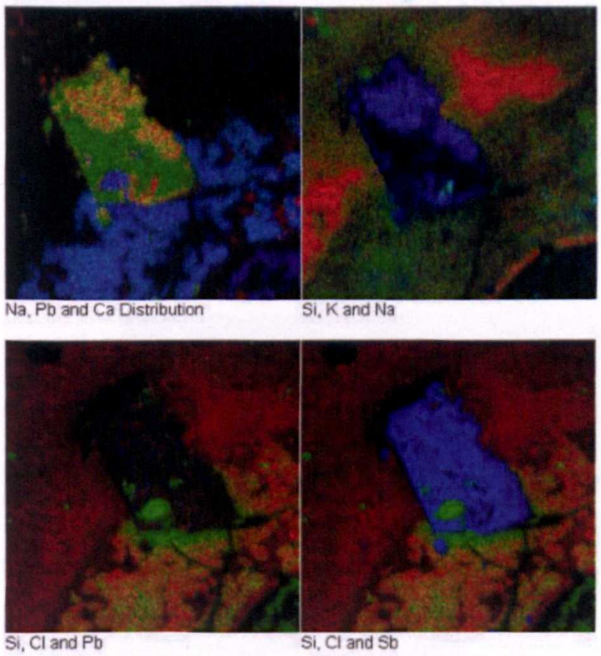

Figure 6.23 Image Overlays to Show the Main Features of Compositional Heterogeneity within Th153.

Showing overlays of the summed images presented above.
Top Left: Na (red);Pb (green); Ca (blue). Yellow area is overlay of Na and Pb.
Top Right: Si (red); K (green); Na (blue).
Bottom Left: Si (red); Cl (green); Pb (blue).
Bottom Right: Si (red); Cl (green); Sb (blue).

A number of smaller inclusions can also be seen in the matrix of Th153, with compositions roughly correspondent to the larger one, at least in the presence of the more highly concentrated (and therefore more visible) Pb and Sb species. A less clearly defined area, surrounding what appears to be a hole, can be seen in the bottom right of the images. This area is enriched in elements which are otherwise associated primarily with either the matrix or the inclusion(s), including Ca, Pb and Na, and is also slightly elevated in K. It may be the result of (probably post-depositional) corrosion, as this tends to involve the enrichment of Na (and other alkalis) and Ca in a certain area following their migration from the matrix (see Newton and Davison 1989, 138 - 139): given that this sample was retrieved from Greece, where burial conditions are more conducive to weathering, this is not surprising. Two Si-rich areas with poorly defined edges are also present to either side of the inclusion. These could be associated with devitrification as a result of corrosion, though in SEM imaging for other samples this was usually identifiable in the form of regular, euhedral crystals, which were not encountered in this sample. It is thus uncertain whether the two areas of heterogeneity are linked, and whether they are related to manufacturing or post-depositional processes, or both.

Figures 6.24 and 6.25 illustrate the positive and negative ion results respectively for major and minor elements in Am2. The analysed area contained a cluster of cubic-form inclusions of corresponding composition. The inclusions were enriched in Sb and Pb, as

well as BiO and BiO_2 (discussed separately below). There is no indication of preferential distribution of these species within the inclusions themselves, either irregular (as for Th267) or indicating growth around a nucleus (as for the calcium antimonate samples). An area rich in Si could also be identified in Am2, and all other signals associated with the matrix (most notably Na and K) were depleted in this area: given the lack of alkalis and the enrichment of Si this area may be the result of devitrification, as with Th153 above.

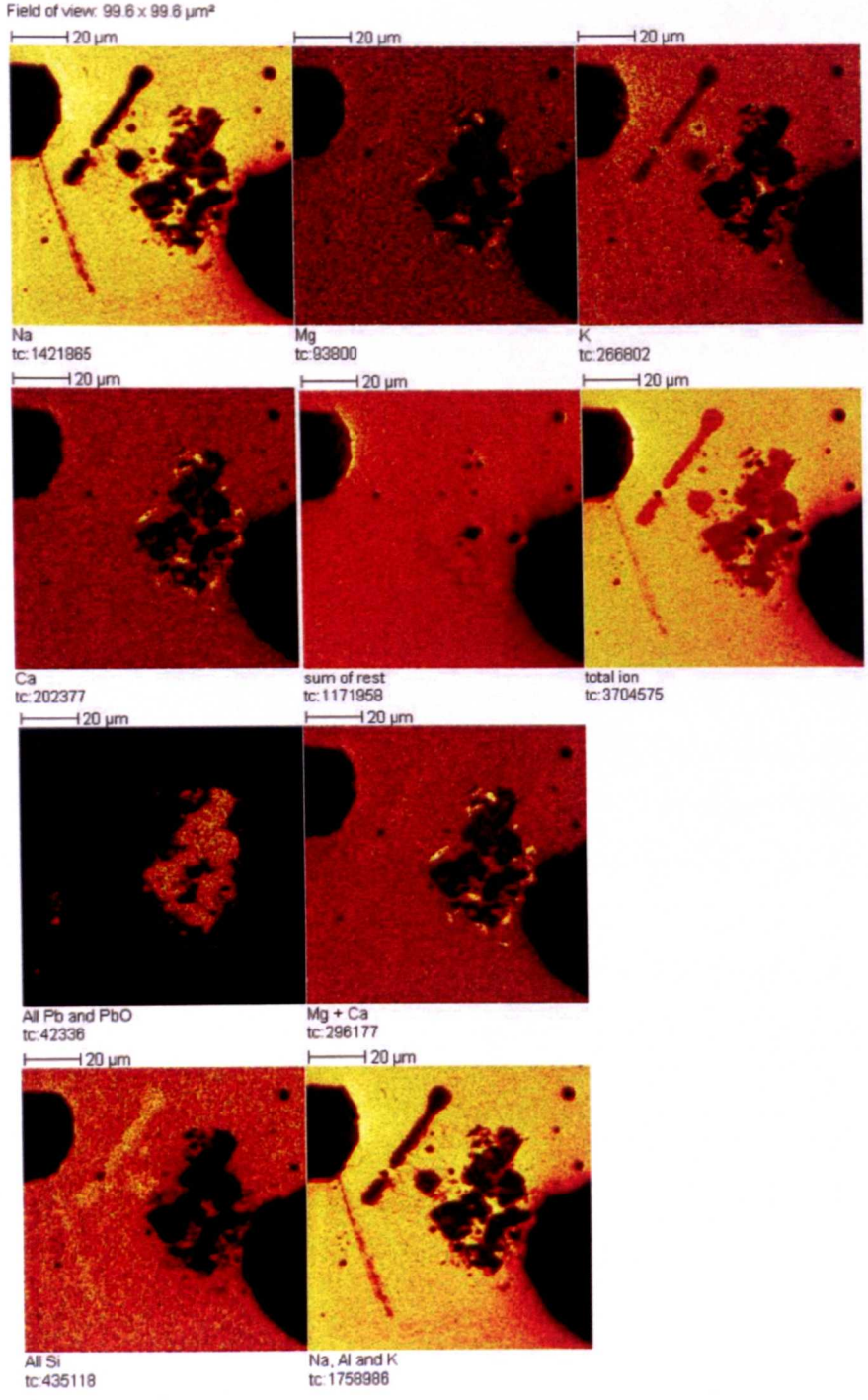

Figure 6.24 Positive Ion Results for Selected Major and Minor Elements in Am2.
'All Pb and PbO' is a summed image for ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{206}PbO, ^{207}PbO and ^{208}PbO.
'All Si' is a summed image for Si, ^{29}Si and ^{30}Si.

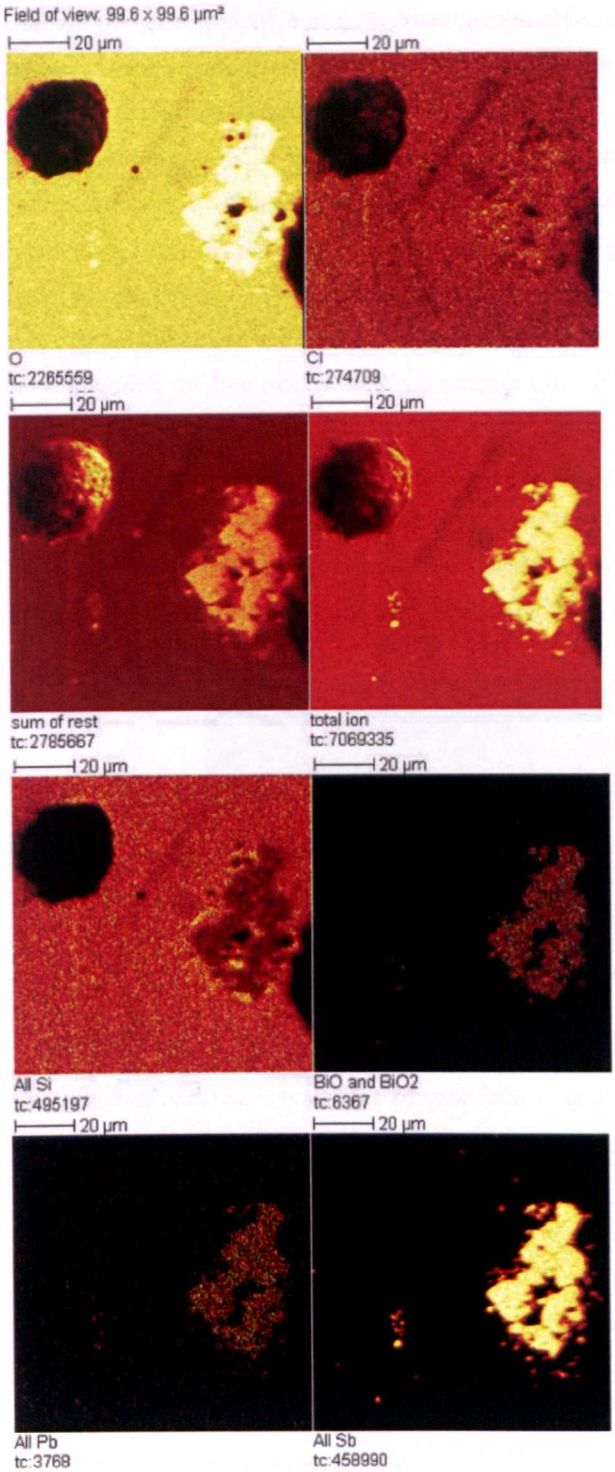

Figure 6.25 Negative Ion Results for Selected Major and Minor Elements in Am2.
'All Si' is a summed image for Si, ^{29}Si, SiO_2 and SiO_3.
'All Pb is a summed image for ^{204}Pb, ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{206}PbO, ^{207}PbO and ^{208}PbO.
'All Sb is a summed image for SbO_2 and $^{123}SbO_2$.

There are also a number of smaller features in the direct vicinity of the inclusion cluster in Am2. Like the clustered inclusions themselves, these are enriched in Sb, Pb and Bi species by comparison with the matrix, but (unlike the inclusions) are also enriched in Mg and Ca, even by comparison with the matrix. The possible origins of these crystals is most visible

through an examination of the summed images given in Figure 6.26: the image on the left illustrates the primary features of the area analysed, based on summed images shown in Figures 6.24 and 6.25 (above), with the unique composition of the small features surrounding the inclusion cluster highlighted; the image on the right shows the relative distribution of Si species by comparison with Mg and Ca species. It is apparent in the latter image that Si is almost completely absent from the area of the clustered inclusions themselves (showing no evidence of zoning associated with *in situ* crystal growth), is most heavily concentrated within the matrix, and is present in a level intermediate between the two in the region of the small features surrounding the matrix, here with no clear edges or other sharp distinction visible. It is thus likely that these smaller crystals, with a less clearly defined morphology than the cubic cluster of inclusions, were formed by precipitation from the melt. Given that they are enriched in Sb, Pb and Bi it is further suggested that they formed from the partial dissolution of the added opacifiers, in combination with those species (Ca, Mg) which were present in the glass melt.

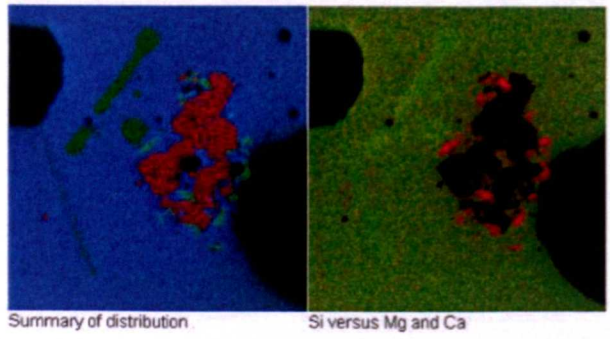

Figure 6.26 Positive Ion Results for Selected (Summed) Major and Minor Elements in Am2.

Left: cubic form inclusion cluster, surrounded by smaller inclusions of different composition.
Right: Si (green); Mg and Ca (red).

Comparison between the matrix and the large inclusions was tested in high resolution mode through the selection of ROIs, of roughly correspondent size, for each. In both Th153 and Am2 the spectra generated from ROIs revealed a marked distinction between the composition of the inclusion cluster and that of the matrix, as is reflected in the images. Figure 6.27 illustrates the relative difference between matrix and inclusion in a portion of the spectrum for Am2, comparable to those shown for other samples above.

The spectra generated from ROIs illustrated that Pb and Bi species were present in higher levels in the matrix of Th153 than of Am2 (an example showing isotopes of Pb is given in Figure 6.28), though the Sb signals in both matrices were relatively low. Coupled with the evidence for partial dissolution of the inclusion in Th153, this suggests that a small amount of the opacifying material was dissolved in the melt and recombined. The smaller inclusions containing Pb and Sb were precipitated out from this, but excess Pb and Bi remained in the matrix. The situation in Am2 appears to have been somewhat different,

perhaps indicating that less dissolution occurred: the small features surrounding the inclusion were only present in its close vicinity, and less relative evidence for the presence of Pb and Bi within the matrix was found.

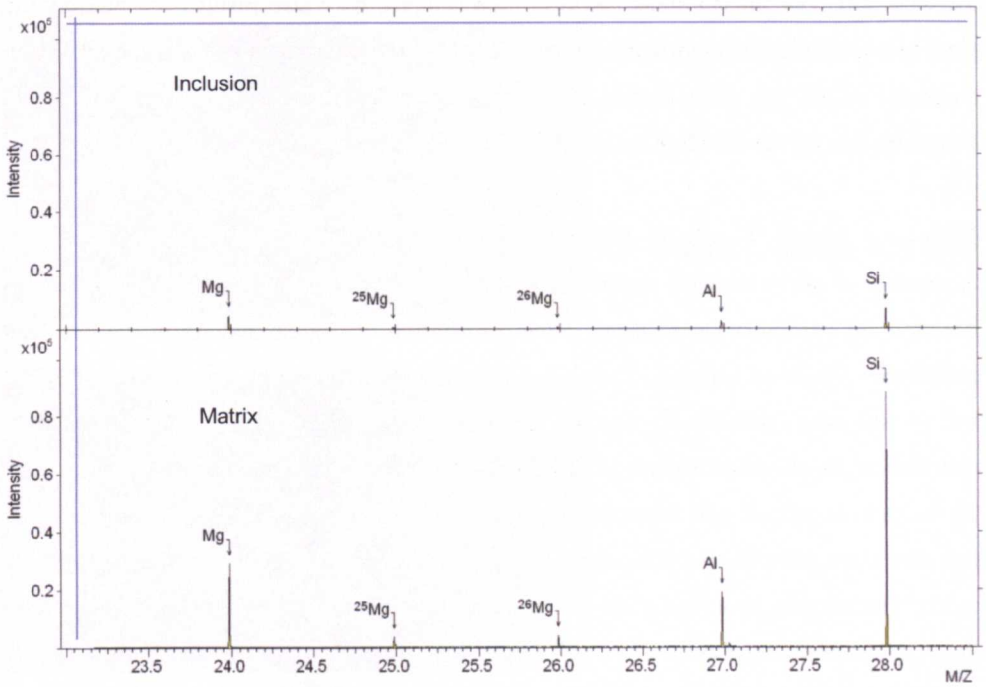

Figure 6.27 High Mass Resolution Spectra for Selected ROIs in Sample Am2.

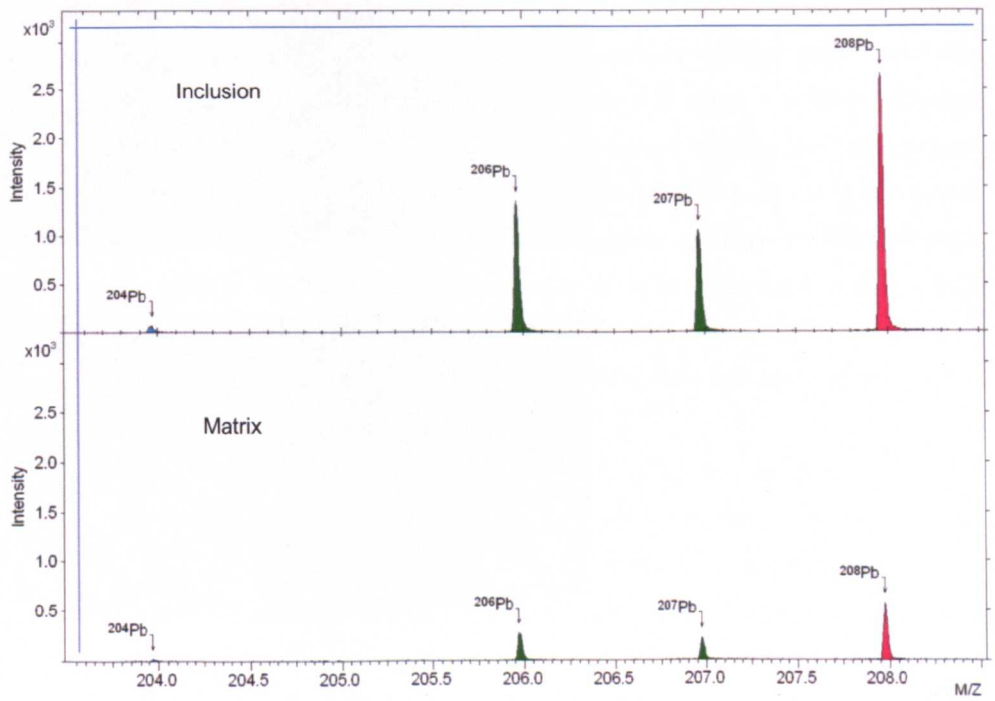

Figure 6.28 High Mass Resolution Spectra showing Pb isotopes in ROIs for the Matrix and Inclusions of Am2.

This difference between the two samples could be explained by the production parameters for adding opacifying inclusions: higher temperature, or more lengthy exposure to high

temperature in Th153 would have facilitated the mobility of those elements associated with the inclusions in the melt. Higher viscosity in Am2, a result of lower temperature, would result in less dissolution and decreased mobility of those elements associated with the inclusion. The Si-rich areas found in both samples may also result from holding the glass at an intermediate temperature, causing partial re-melting and reformation of certain elements within the glass matrix, including some of those (such as Pb) which had dissolved into the surrounding matrix from the added inclusions themselves.

Minor and Trace Elements

A number of lower strength signals associated with trace and minor elements were also detected. Of particular significance is the distribution of Co, Sn and As in the two lead antimonate opacified samples. These were initially investigated by comparison of ROIs, but it was also possible to produce high mass resolution images illustrating their distribution, as shown in Figure 6.29. Shortland (2002, 525) has suggested that a 'similar' Sb:As ratio in yellow and white opaque glasses (0.006:1 and 0.008:1 respectively) may indicate a consistent use of antimony from the same source in the production of lead and calcium antimonate opacified glass. For As, only clean peaks for AsO_2 could be identified: this was found to be present in all samples in low quantities, but was only preferentially distributed in the two lead antimonate opacified samples. This is perhaps to be expected, given the similarity between matrix and inclusions in the calcium antimonate opacified samples and the low abundance (and therefore definition of AsO_2), but it is interesting to note that where As *was* preferentially distributed – i.e. in the two lead antimonate opacified samples – it was associated not with the inclusions, but with the matrix. This suggests that As was not brought into the glass with antimony, but with one of the ingredients of the glass in the matrix. Elemental As could not be separately distinguished from CoO due to extensive overlap between the two peaks: the 'CoO' images in Figure 6.29 may thus represent a combination between As and CoO (both of which are known to be present in the samples in trace levels on the basis of SEM and EPMA). In any case, this As / CoO signal was also associated with the matrix rather than the inclusions.

Sn was found to be present in very low quantities in both lead antimonate opacified samples, and again appears to have been associated with the matrix (also shown in Figure 6.29). The presence of Sn in samples coloured by copper such as the calcium antimonate opacified sample Brak12 may indicate the use of scrap bronze as a colorant. It could not be confidently assigned in either the white or the turquoise calcium antimonate opacified samples, however, and it is possible that this was due to the coincidence of stronger (most

probably organic) peaks with those of Sn, as it had been detected with SEM[70] in both calcium antimonate opacified samples.

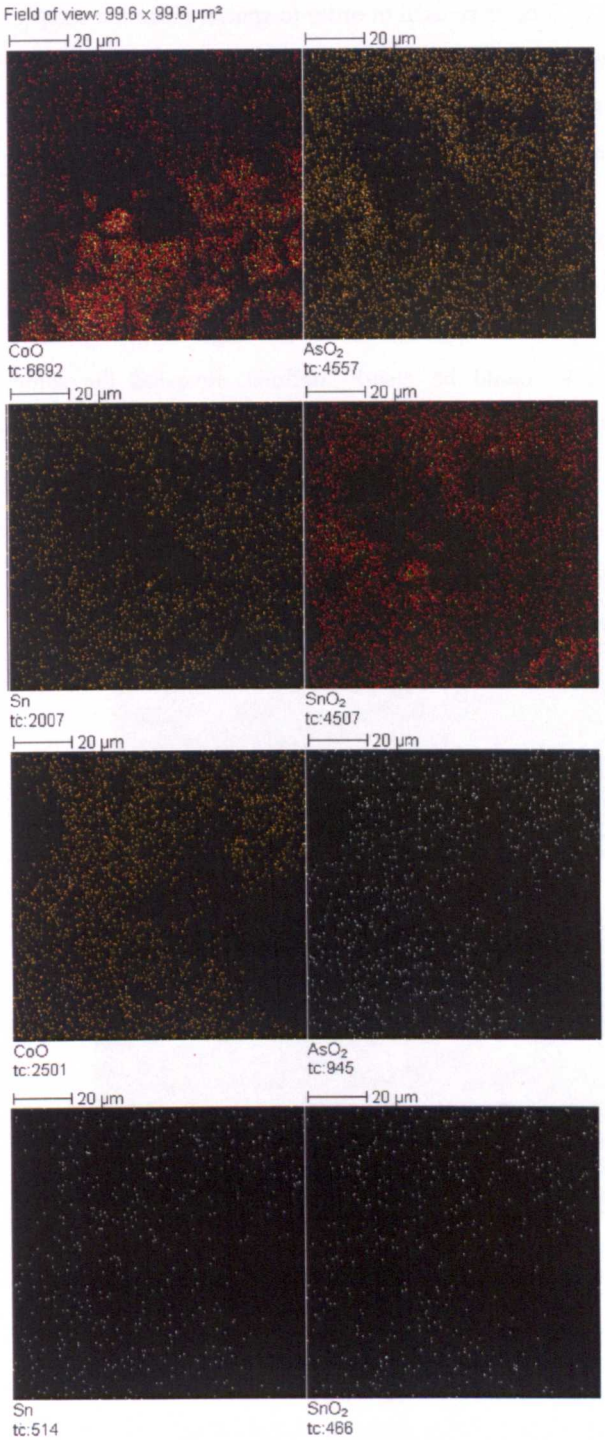

Figure 6.29 Positive Ion High Mass Resolution Results for Selected Trace and Minor Elements in Th153 and Am2.

Top two rows: Th153.

Bottom two rows: Am2.

[70] Though it is possible that the SEM results were erroneous, it is perhaps more likely that it was present but not detected in EPMA: difficulties with detecting Sn with this technique were also encountered in the present study, as noted in Chapter 5.

The presence of Bi, BiO and BiO_2 was detected in all samples. Because a Bi ion source was used, however, the evidence required careful examination before it could be verified. In particular, it should be noted that Bi ions were used in order to sputter clean the sample surface at several intervals during analysis, as discussed in the methodology, at a higher dose than the subsequent analysis. Indeed, elemental Bi was found to show no preferential distribution but was present in equal amounts across the sample surfaces. Its oxides BiO and BiO_2, however, were highly concentrated within the inclusions in the two lead antimonate opacified samples, particularly apparent in the negative ion results. It should be noted that BiO_2 suffered slight contamination in the high spatial resolution mode due to the proximity of a small, unknown peak but examination of the high mass resolution images and spectra, where the peaks could be clearly defined, revealed the same distribution for BiO_2. The co-location of oxides of lead, antimony and bismuth is illustrated in Figure 6.30.

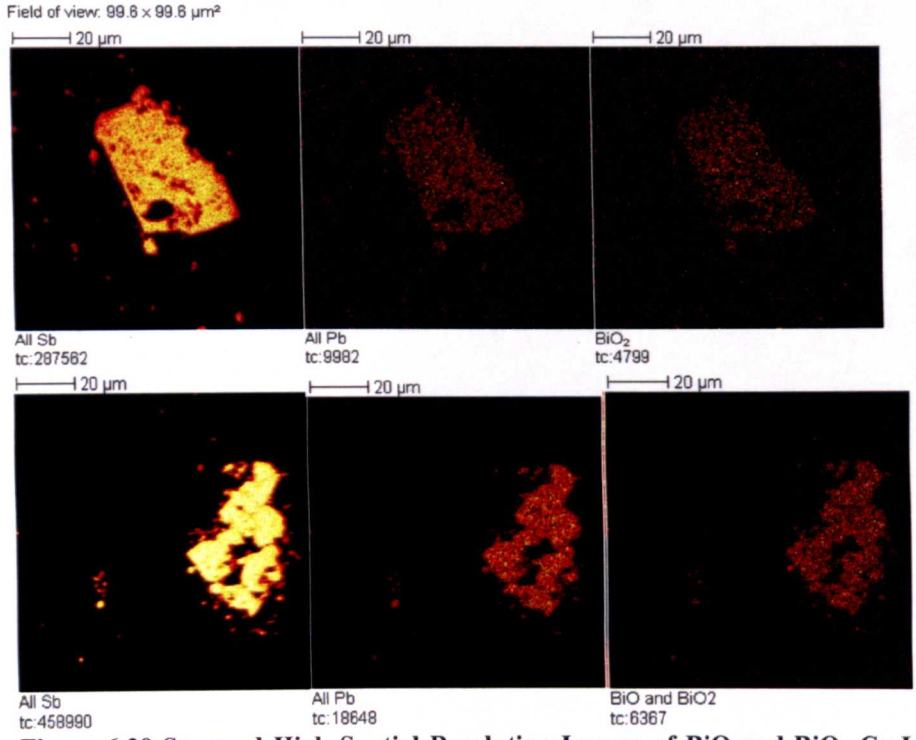

Figure 6.30 Summed High Spatial Resolution Images of BiO and BiO_2 Co-Located with Oxides of Sb and Pb.

Top: negative ion images for Th153. Left: SbO_2 and $^{123}SbO_2$. Centre: ^{206}PbO, ^{207}PbO, ^{208}PbO, $^{206}PbO_2$, $^{207}PbO_2$ and $^{208}PbO_2$. Right: BiO_2.

Bottom: negative ion images for Am2. Left: SbO_2 and $^{123}SbO_2$. Centre: ^{206}PbO, ^{207}PbO, ^{208}PbO, $^{206}PbO_2$, $^{207}PbO_2$ and $^{208}PbO_2$. Right: BiO and BiO_2.

BiO and BiO_2 were present in far lower quantities in the calcium antimonate samples, as illustrated (for the BiO_2 peak) in Figure 6.31. The oxides are highly unlikely to have formed during sputtering and their presence suggests that we may reasonably argue for the association of Bi with the inclusions in the two lead antimonate samples. Similarly, the evidence for preferential distribution and the difference between the samples opacified

with lead antimonate and those opacified with calcium antimonate supports the suggestion that the co-location of BiO and BiO_2 with Pb and Sb species is relevant to the chemistry of the colorant-opacifiers originally added to the glass[71].

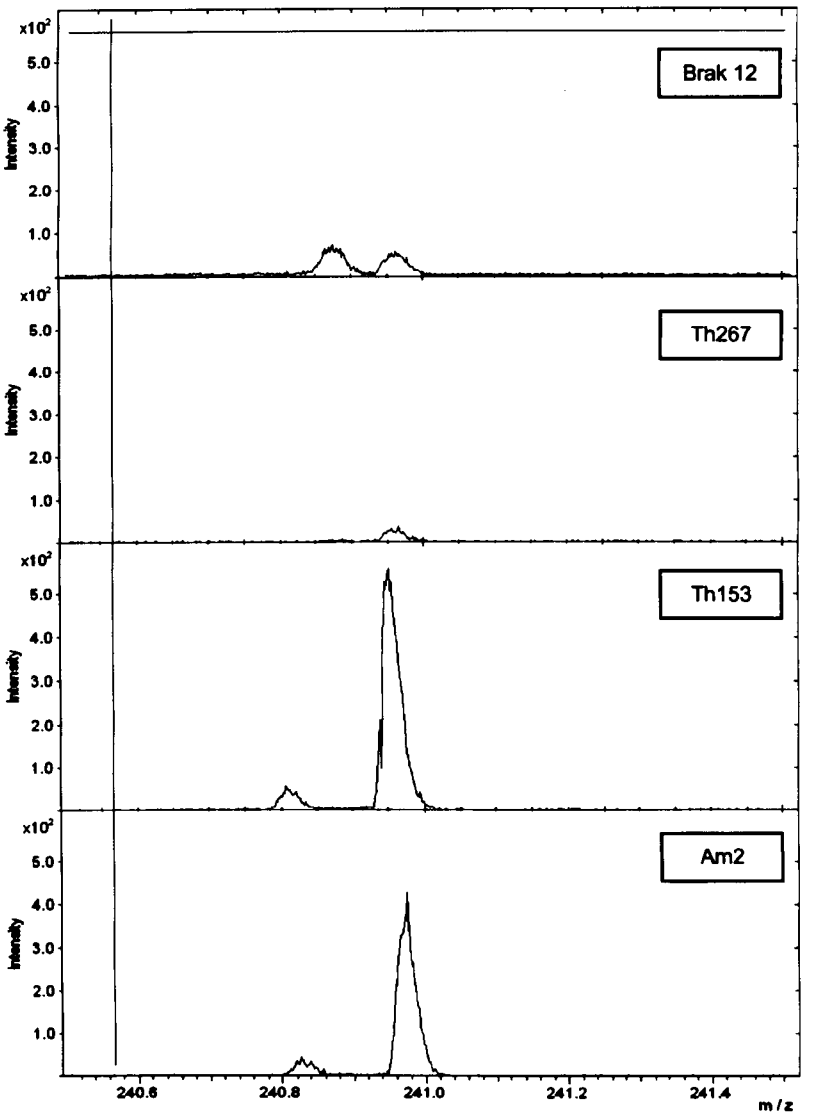

Figure 6.31 BiO_2 in Negative Ion, High Mass Resolution Spectra.
The intensity of the peaks for BiO_2 are compared between the four samples: they are significantly more intense for the two samples of lead-antimonate opacified glasses shown at the bottom.

The isolation of S species, on the other hand, was particularly difficult even in high mass resolution mode, as the peaks for S coincide with those for species of O. In particular, the peak for elemental S was strongly contaminated by the much larger O_2 peak (shown in the

[71] It should also be noted that the oxide signals in general, as can be seen in the negative ion images, were enriched in the area of the inclusion, so that the concentration of Bi oxides in the same area *may* be related to the surrounding chemistry. In the highly heterogeneous sample Th153, however, Bi oxides are almost exclusively associated with the large inclusion itself, and the signal does not show any preferential distribution within the other areas of the heterogeneous matrix, whereas O species do, as can be seen in Figure 6.22.

negative ion images discussed above). Similarly, HS, SO, and SO_4 were all detected but the first two were in close proximity to species of O (O_2H, CHOF). This contamination precluded the production of meaningful high spatial resolution images. Figure 6.32, however, shows high mass resolution images for oxides and hydrides of S, and for O_2. It is apparent that S is distributed differently to the O_2, and that this distribution is followed by the hydrides and sulphides of S (all of which are summed in final image shown). The results for Am2 were less clearly distinguishable, as both O_2 and the signals associated with the species of S were found to concentrate within the inclusion cluster with no visible internal differentiation.

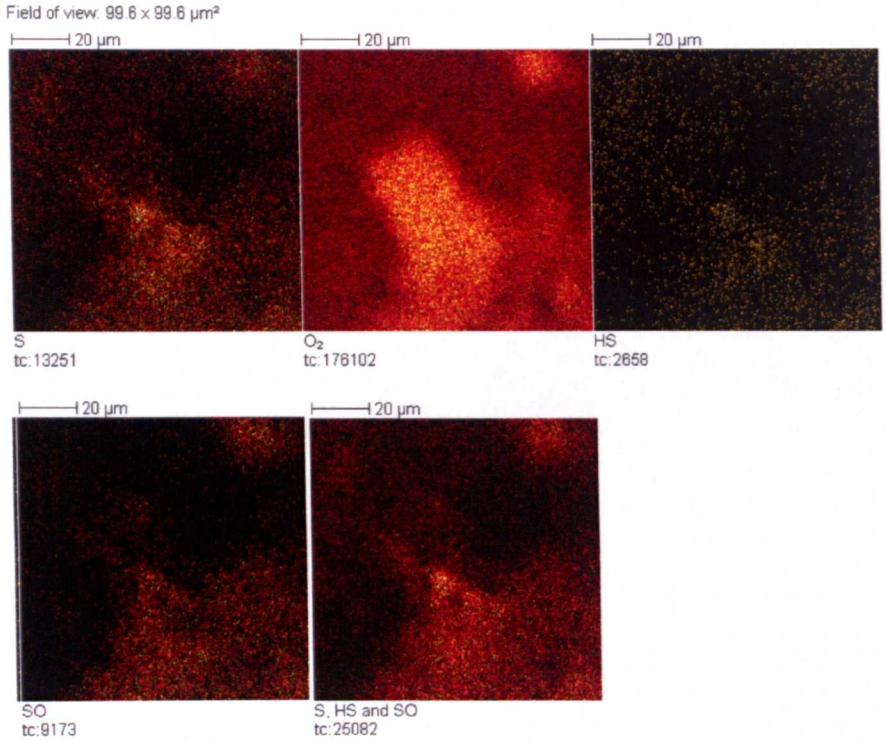

Figure 6.32 Negative Ion High Mass Resolution Images Showing Distribution of S and O_2 within Th153.

Difficulties were also encountered in the isolation of those peaks relating to Zn, and again it was not possible to produce uncontaminated high spatial resolution images, due to the close proximity of Zn and S species. The location of the three main isotopes of Zn is thus illustrated in high mass resolution mode, for Th153 in Figure 6.33. In comparison with Figure 6.32 discussed above, it can be seen that Zn and S, though present only in small amounts, are concentrated within the same area. Interestingly, they are both most strongly co-related within a particular region of the inclusion in Th153. Similar results were found for Am2, though as above they were less clearly distinguishable, in part due to the lesser heterogeneity of the area analysed (and the consequent difficulty of discerning using images to support assignation of peaks). The summed results for the location of S species

in Am2 are shown in Figure 6.34 (the Zn peaks could not be resolved well enough to produce an uncontaminated image).

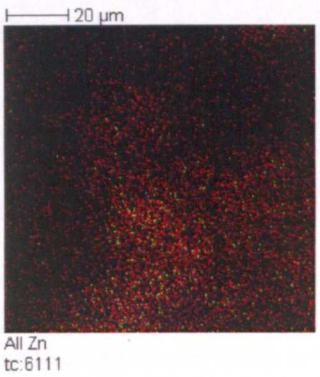

Figure 6.33 Negative Ion High Mass Resolution Image Showing Distribution of Zn within Th153.

Summed image for Zn (Zn, ^{66}Zn and ZnO).

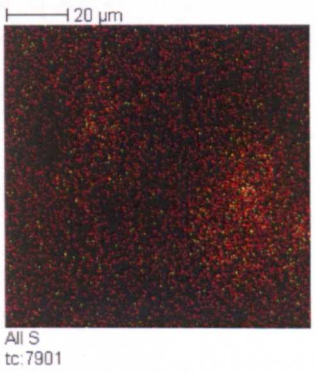

Figure 6.34 Negative Ion High Mass Resolution Image Showing Distribution of S in Sample Am2.

Summed data for oxides and hydrides of S (S, HS, SO, SO_4)

Cu was identified in both matrix and inclusion of Brak 12. Although it could not be isolated in high spatial resolution mode due to contamination from unassigned organic peaks, its characteristic relative isotope distribution allowed it to be confidently identified in examination of high mass resolution data from the ROIs. It was apparent that no preference for either matrix or inclusion in the distribution of Cu could be identified. This lack of preferential distribution between inclusion and matrix is consistent with the precipitation of the opacifying inclusions from a homogeneous melt. Cu was also present as a trace impurity in the two lead antimonate opacified samples, and spectra from ROIs revealed that it was associated with the matrix rather than the inclusions in these. Although it was not possible to produce high spatial resolution images for Cu and its oxides, high mass resolution images shown in Figure 6.35 illustrate the primary association of Cu with the matrix in the two samples of lead antimonate opacified glass.

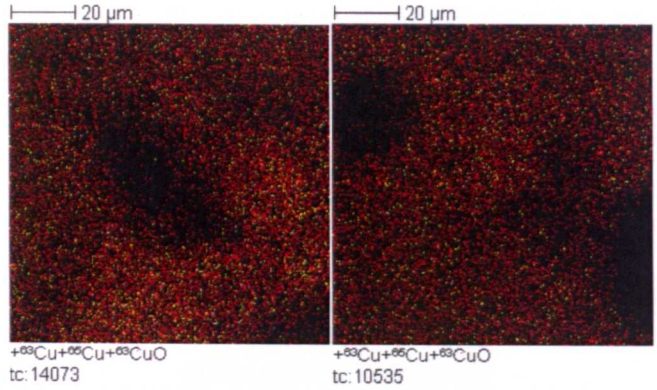

Figure 6.35 Positive Ion High Mass Resolution Results for Cu in Th153 and Am2. Summed images for Cu isotopes and the major isotope of CuO for Th153 (left) and Am2 (right).

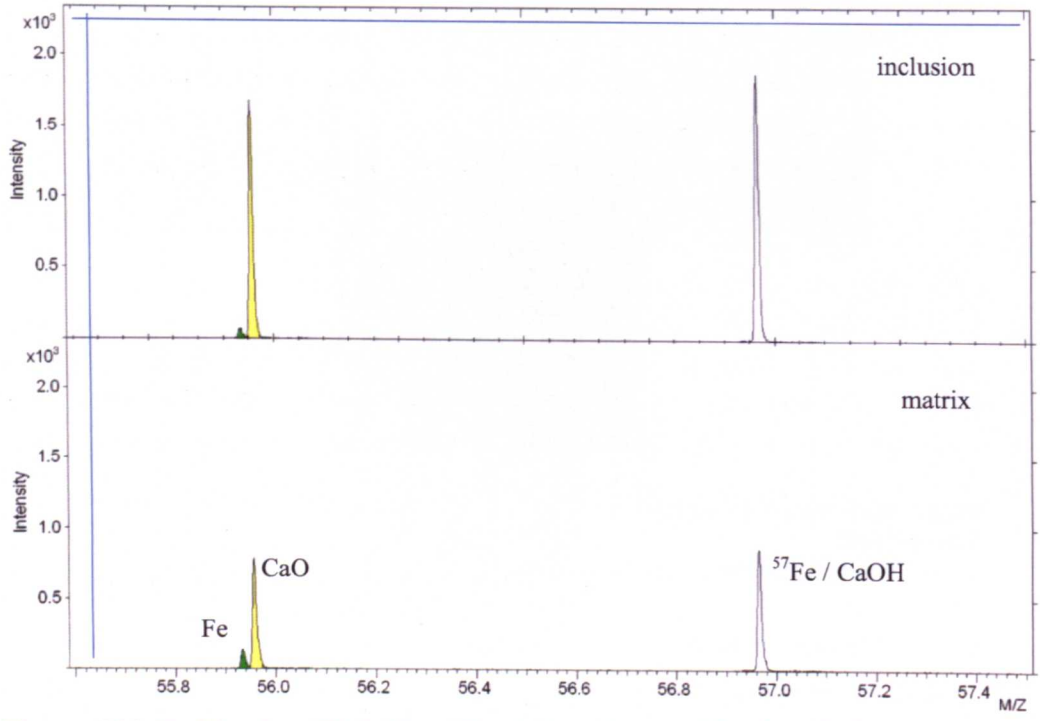

Figure 6.36 Positive Ion High Mass Resolution Spectra Showing CaO, Fe and coincident ^{57}Fe / CaOH in the Inclusion and Matrix of Th267.

Figure 6.36 shows the particular portion of the Th267 spectra for matrix and inclusion in which CaO, Fe and ^{57}Fe are situated. As shown, however, the identification of Fe in the two calcium antimonate samples was problematic as its major isotope was present in far lower quantities than ^{57}Fe. This is probably due to the coincidence of this peak with the much larger CaOH. The ^{56}Fe peak, however, was more clearly distinguishable and – as this isotope of Fe makes up 91.7% of its relative abundance in nature – was taken as the main signal of the presence of Fe, though the distinction between this peak and the larger CaO peak was not clean enough to allow high spatial resolution imaging. Ca and Fe species were in any case found to co-locate in both calcium antimonate opacified samples, with a slightly elevated concentration within the area of the inclusion. The presence of low

levels of Fe in co-location with the concentrations of Ca and Sb in both samples cannot, however, be taken as an *a priori* indication of common raw ingredients: given the low level of Fe in most glass due to its presence as an impurity in silica sources, its concentration within the inclusions is probably a result of preferential precipitation from the melt rather than a reflection of its original chemical associations. Similar issues were encountered in the identification of Fe in the lead antimonate opacified samples. Here, however, the low signal for 56Fe was found to be associated with the matrices rather than the inclusions.

Sources of Opacifiers

It has previously been suggested that an impurity of Bi in opaque glasses could illustrate the use of bindheimite $Pb_2(Sb,Bi)_2O_6(O,OH)$ as a source of lead antimonate (see Henderson 2001). Bindheimite is common in the oxidised portions of lead-bearing antimony deposits, but is rarely found in large amounts. These do not occur in Egypt or western Asia, but bindheimite is known to occur in exploitable quantities in Italy[72] (Mineral Data Publishing 2001 - 2005). It has also been recently identified in lesser quantities in south-eastern Turkey, a result of surface oxidation of listwaenite (see Çolakoğlu 2009, 69). Brill (1970) has suggested that the mineral was an article of trade during the Late Bronze Age.

It should be noted that both lead antimonate opacified samples are thought to derive from Egyptian glasses: the sample from Mycenaean Thebes was taken from a vessel fragment which is stylistically consistent with Egyptian material and is thus thought to be an import. It must be noted, however, that no Bi was detected in the opaque yellow sample from Amarna which was analysed in the pilot study (Rutten et al. 2009, 973), though it is possible that the changes in experimental parameters have improved its detection.

Shortland (2002, 524) has argued that, if found, the presence of Zn and S impurities in glass could relate to the use of galena (PbS) from the Red Sea coast, 'presumably' with significant amounts of spheralite (ZnS) to account for the Zn (though ZnS is not exclusive to this source of lead). The presence of Zn and S in Th153 and possibly Am2 is not surprising, given their previous identification in archaeological samples of the same composition using other analytical techniques. But their co-location in opacifying inclusions has now also been identified and considering the evidence for the low temperature addition of lead antimonate opacifiers discussed above, they can be reasonably confidently associated with the source of lead, antimony or both.

The additional presence of BiO and BiO_2, also co-located strongly with Pb and Sb species, however, complicates this pictures somewhat. Bi, Zn and S can be encountered in ore

[72] As well as the Far East, Sub-Saharan Africa and the New World.

deposits containing Pb and Sb, and such deposits show a remarkable degree of heterogeneity in nature, so sampling and analysis of ores does not always reveal the full range of compositional possibilities. Indeed, the study of south-eastern Turkish occurrence of bindheimite mentioned above (Çolakoğlu 2009) indicates that Zn and S were also present in the same deposits, so they *may* be indicative of the source of both lead and antimony.

It is also possible that bindheimite was used along with additional lead (and the high lead to antimony ratio of yellow opaque glasses from Amarna, discussed in Chapter 5, seems to favour this suggestion). If two different sources of lead and / or antimony were included they must have been sintered together before addition to the glass, to account for the co-location of these elements within inclusions with clear crystal faces. It is perhaps more difficult to account for the preferential distribution of Zn and S *within* the inclusion in Th153: the irregularity of this distribution suggests that it certainly does not indicate preferential growth from the melt, but whether it is associated with the combination of various ingredients through sintering, or to their heterogeneous distribution within a mineral or associated ore cannot be determined at the present stage.

Discussion

The precise stages of production of LBA glass – in particular with relation to the addition of colorants and opacifiers – have yet to be agreed upon. This is in part due to the difficulty of establishing the precise location from which various signals are generated from within the sample with more conventional analytical techniques, as discussed earlier in the present chapter, which precludes a detailed study of the formation process of any given inclusion or feature. Although authors such as Shortland (2002; Shortland and Eremin 2006) have managed to draw reasonable conclusions on the basis of quantitative chemical information and occasionally reference to BSE images taken with electron microscopes (a more detailed examination of which has been undertaken in the present work: see Chapter 5) a number of questions related to manufacturing technology and raw ingredients provenance are still open to debate. The ability to distinguish between the associations of elements within the glass matrix and the inclusions, in particular in yellow opaque glasses (the inclusions in which seem to retain the composition of the added opacifiers), is necessary to fully address these questions. Equally importantly, however, is the presence (or lack) of heterogeneity within inclusions themselves. ToF-SIMS directly addresses these issues, crucially with trace element sensitivity. Some suggestions on the nature of production processes involved in creating opaque glass are thus offered below: future study with ToF-SIMS, avenues for which are also recommended below, will provide a broader base from which to draw firm conclusions.

One of the key identifiable differences between the samples is between the composition of the inclusions and that of the surrounding matrix. In Th267, which was coloured and opacified by calcium antimonate, the matrix composition was almost the same as that of the inclusions, the main difference being the relative quantities of each element or compound in the two areas. In Brak12 too, the calcium antimonate based opacifiers appear to be closely related to the composition of the melt. This is particularly interesting as Brak12 is a sample of turquoise glass: the lack of heterogeneity and compositional similarity between matrix and inclusions suggest that – whether two previously formed colours of glass were combined, or whether a colorant or opacifier was added to one pre-formed colour (see Chapters 3 and 5) – all ingredients were reduced to a completely molten state before the temperature was reduced and crystallisation allowed.

In Th153, by contrast, matrix and inclusions are almost entirely compositionally exclusive, although both appear to have contributed to the anomalous Ca-rich feature. Am2 also illustrates a clear distinction between the composition of the matrix and that of the inclusions and here again there is an example of what appears to be a combination of the two, in the small features surrounding the inclusion cluster. It is thus suggested that the yellow opaque glasses were not formed by direct precipitation from the melt.

Seemingly against this interpretation, however, is the euhedral, cubic form of the larger lead antimonate inclusions, which has previously been cited as evidence for slow precipitation from the melt, their regular form precluding the suggestion that they were crushed and broken as would be expected before addition to a glass batch (see Mass et al. 1998, 121 - 133). ToF-SIMS, however, has revealed that there is no indication of the regular, outward zoning within the crystals which is associated with *in situ* crystal growth. The cubic form inclusions in Am2 may be too small to reveal internal heterogeneity, or may be homogeneous, but the larger example in Th153 clearly illustrates internal heterogeneity which has no indication of growth around an initial nucleus of precipitation from the melt. Shortland (2002, 524–525) has also tentatively suggested that lead antimonate opacifiers were not fully dissolved in the melt, on the basis of the uneven distribution of inclusions within some samples of yellow-antimonate opacified glass from Amarna, with reference to BSE images collected during SEM.

There are two alternative explanations to formation from a homogeneous melt. The first is that these crystals may have been added from a source which contained both lead and antimony. The second possibility is that they were formed in a primary stage involving the sintering together of those ingredients which would contribute to colour and opacity. A similar situation was suggested for the yellow opaque sample analysed in the pilot study, on the basis of elevated Fe within the inclusion (Rutten et al. 2009, 973).

Furthermore, the presence of silica crystals in both yellow opaque samples analysed may indicate that the glass was held at an intermediate temperature (presumably something below the melting point of a mixture of Pb and Sb oxides at 850°C: see Shortland 2002, 524) for an extended period of time so that some of the silica was able to overcome the viscosity of the melt and crystallise (see Chapter 3 for a discussion of glass cooling and formation). In order to allow the added preparation to be dispersed relatively thoroughly throughout the pre-formed glass it would need to be held at an intermediate temperature which was high enough to facilitate enough fluidity in the glass to allow mixing, a minimum of 505 – 590°C (viscosity approximately 10^{14} poise), based on working temperatures (Stern 1993, 30), but which was not necessarily high enough to allow complete melting (at least 940°C for a pre-formed glass: see Stern 1993, 22 - 23). As noted above, the temperature and / or length of heating time for the two lead antimonate samples may have been different, due to the distribution of re-precipitated material and the degree of dissolution of Pb and Bi within the matrix. It would be interesting to use ToF-SIMS in future analysis in order compare these findings with a number of lead antimonate glasses experimentally produced under laboratory conditions at various temperatures.

It is further argued that the distinction between lead and calcium antimonate opacified samples is based not only on manufacturing technology but on the source and preparation of raw materials. Despite previous suggestions that As can be used as an indicator of a shared antimony source between lead and calcium antimonate opacified glasses, AsO_2 was found in samples Th153 and Am2 to be associated not with the inclusions but the matrix. It is thus possible that either a different source of antimony was used in the production of yellow and white opaque glasses, and / or that complex preparation of the opacifiers before addition to the glass was practised. Because it has not been possible in the context of the present study to ascertain whether the calcium antimonate sample from Mycenaean Thebes (Th267) was manufactured in Mesopotamia or Egypt[73], it could be argued that the differences in levels of Bi between the two are not significant in terms of coloration and opacification. On the other hand, it should be noted that antimony ores or minerals containing antimony are not commonly found, and are likely to be articles of long distance trade: thus the difference in signatures between the lead and calcium antimonate opacified samples is significant whatever their location of primary production.

Though in all cases further research is needed in order to clarify and extend the suggestions offered here, it is apparent that ToF-SIMS is uniquely placed to address such issues as the proposed association between certain elements and raw ingredient sources. This is particularly important when combined with the arguments presented in Chapter 5,

[73] Am2 and Th153, despite being found in different locations, are both thought to have been the product of Egyptian glass production (see Appendix 1). As Th267 is from Mycenaean Thebes, it could have been made in either Egypt or Mesopotamia (see Henderson et al. 2010; Shortland et al. 2007).

as it appears that LBA glass production was somewhat more complex than may previously have been assumed. These issues are returned to in Chapter 7.

Regional diversity between compositions and manufacturing technology must also be investigated with ToF-SIMS. This will require the examination of a larger sample set than has been possible in the context of the present study. Previous isotopic analysis has indicated that Nd and Sr could be used as markers of provenance (Henderson et al. 2010). Sr was identified in the present study, though no thorough investigation of the presence of Nd was undertaken. Ratios between a number of trace elements have also been associated with distinctions between regional provenance (Shortland et al. 2007) and some of these were tentatively identified here (Zr, Ti and Sc). The full investigation of the relevance of these signals, however, requires quantification (see below).

Optimisation, Issues and Avenues for Future Work

The necessity of acquiring and analysing data in both high mass and high spatial resolution modes in ToF-SIMS has been illustrated above. In addition, the collection of both positive and negative ion signals has been demonstrated to yield a much larger volume of data: although the positive spectra tended to be most information-rich, certain elements and compounds could only unequivocally be detected in the negative ion spectra. Oxides in particular were generally better represented by the negative ion signals, as were the higher atomic weight elements such as Pb, Bi and Sb: with reference to calcium antimonate opacified glass, Rutten et al. (2009, 975) have already noted that elemental Sb in general gives a higher yield of negative ions compared to positive ions. In some instances, interference between peaks meant that while a particular element and its isotopes were present, only certain of its signals could be mapped. Again, the use of both positive and negative ion spectra offered a broader basis from which to assess the presence of various species. It is suggested that in future work imaging software could be used to summarise (in single images) the data from negative and positive ion results of the same species in order to enhance mapping capability. This would be particularly beneficial for those species which are detected both in elemental form (usually in the positive spectra) and in oxide form (usually in the negative), such as Pb.

The inclusions selected for the present study have been to some extent exceptional: in order to retrieve the maximum information possible from a small area, larger inclusions or agglomerates of inclusions were deliberately selected. As a large part of the aim of the study presented here has been to test and develop the potential of ToF-SIMS for the analysis of archaeological samples of glass, it was decided that the analysis should focus on those inclusions from which the most information could be extracted. There is another reason, however, that larger inclusions or agglomerates may be more useful: where trying

to establish processes of crystal formation (important for both an understanding of production processes and an examination of factors associated with provenance) the larger crystals can provide more clearly defined evidence on the stages in crystal growth from nucleus to edges (zoning). ToF-SIMS is a high resolution technique, but some signals are so weak that patterns are difficult to determine within smaller inclusions. To avoid bias resulting from this the smaller inclusions surrounding a larger inclusion have also been carefully examined, in order to ascertain whether they correspond compositionally with the larger one, as noted above.

In terms of the experimental parameters, it should be stressed that, so far, the primary ion dose has not been experimented with: a more thorough investigation is suggested into the analysis of ancient glass in order to ascertain the maximum dose (and therefore the greatest enhancement of the signals detected) which can be applied to samples of ancient glass before excessive disruption of the surface chemistry. As well as providing improved detection of trace elements and their relative distribution within the areas analysed (both within maps and in ROI spectra), this would provide a better grounding for the quantification of ToF-SIMS results using glass standards. The latter development, already achieved by Rutten et al. (2009), allows not only the provision of quantifiable trace element data, but has the potential for the characterisation of material based on isotopic signatures. The ability to discern the signals from inclusion and matrix, in lead antimonate opacified samples in particular, coupled with the use of quantified isotopic data, has enormously powerful potential for the study of ancient glass. The source of opacifiers and matrix ingredients could be more thoroughly investigated and discussed, and these could be compared in samples from a broad range of contexts, allowing a detailed distinction between the provenance of those raw ingredients associated with the bulk glass and those associated with the opacifying inclusions.

7. Discussion and Conclusions

> "An interesting feature of glass beads is that ... they were often made deliberately to imitate natural stones ... In that respect they may truly be regarded as an early example of much in contemporary life that is (often negatively) viewed as the product of an all-pervasive artificiality."
>
> Lidia Sciama (1998, 6)

> "The exact experiences of people in the past may well elude us, but the ways in which they set up worlds that made sense to them is available to us through an appreciation of the sensory and social impacts of the objects that formed the fabric of past lives."
>
> Chris Gosden (2001, 167)

As noted in the introduction, one of the primary aims in undertaking the research presented has been to provide a comprehensive picture of glass in Late Bronze Age Egypt from the perspectives of chemical, archaeological and textual analysis in order to reconstruct the processes involved in glass production, its organisation, the motivations behind the demand for glass, the relationship between these factors and colour, and its perception as a material. These issues are now returned to, and a set of specific questions are addressed by recourse to a combination of the evidence in the preceding chapters.

Classification of Glass as a Material

Timothy Taylor (2005, 197) summarises a key dilemma in the interpretation of materials, and a materiality-based approach in general: 'in order to interpret something I will already have formed some idea of what it is ... The possibility of understanding anything new and surprising is dramatically lessened'. Before relating this dilemma to glass, I wish to note that I maintain that the primary aim of archaeology should be to develop an understanding as close as possible to past reality, however many obstacles may stand in the way (not least the theoretical difficulties of ascribing such a loaded meaning as 'reality' to something as intangible as the past). So discovering something 'surprising' should not be – although of course it frequently is if we consider the nature of academic funding and publication – the primary aim of archaeological endeavour. Nonetheless, the ascription of any material, including glass, to a single category has to be rigorously examined before it is applied freehand to models of the past, not just those of perception but also of production, trade and consumption of the material.

The arguments presented in Chapter 4 have illustrated that we may reasonably assume 'glass' to function as a distinct category of material in the Late Bronze Age, but that the importance of colour and the (perceived) material associations between glass and other materials are also of vital consideration. More damaging, perhaps, to our understanding of the perception of glass, is its often unqualified description as belonging primarily within the modern category of 'vitreous materials'. Technological analysis has already marked vitreous materials in the Late Bronze Age as the products of distinct production

technologies if not always distinct raw materials (see Rehren 2008), and contextual archaeological evidence does not indicate strong links between glass and faience, aside from their presence at locations of (usually high temperature) craft working, in which numerous other materials are also found. The difficulty in testing our own categorisations of course remains, but it is suggested here that by examining a broad range of technological, textual and contextual evidence, we may reasonably infer the category into which glass as a material was slotted.

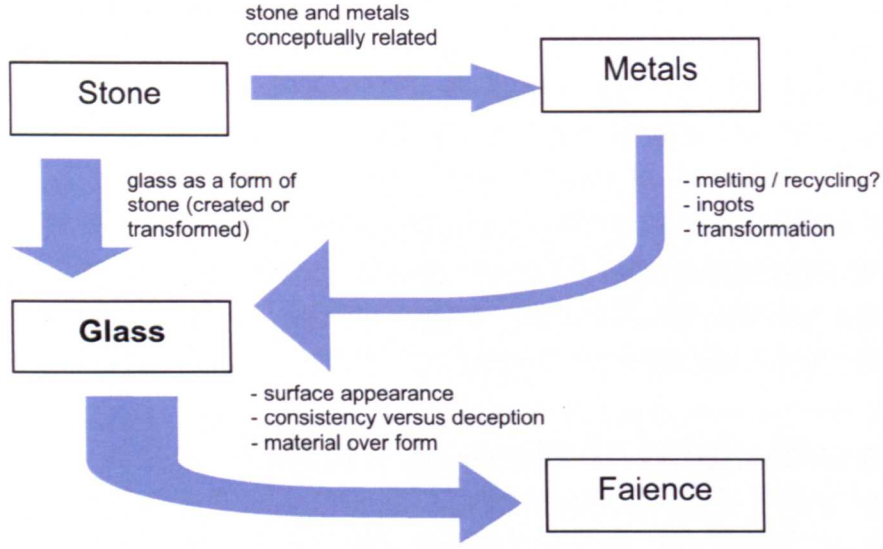

Figure 7.1 Schematic Summary of the Relationship Between Glass and Other Materials.

Figure 7.1 provides a schematic summary of the key relationships between glass and other materials, as argued for here. The evidence suggests that glass was seen as a form of precious stone, but was also understood as a distinct material on the basis that it could be melted. The consistency of glass, in particular, marked it apart from faience, as did its potential for recycling. Glass vessels and some small items were deliberately worked into patterns too regular to be found in stone, sometimes with the deliberate application of technologically demanding raised decoration (though this is more common in Mesopotamia than Egypt), and early glass vessels in particular were made in larger sizes than those of stone, thus *highlighting* the created nature (artificiality) of glass, rather than attempting to replicate the visual properties of stones. Finally, glass may have been conceptually linked to metals as it could be re-melted and worked while hot, a property which may have been emphasised by the trade of glass in ingot form.

Glass, stones and metals may not have shared the same production technologies, but – as noted above – there are a number of factors which unite them as 'raw' materials. Stones

and metals were already conceptually related[74] as they may be seen to have intrinsic value. There is no reason, however, to assume that glass did not fit readily into this pattern. After all, metal ore (which is anyway visually and physically associated with stone) requires treatment (smelting) before it can be traded in workable form, as does glass. Similarly, precious stones and precious metals are physically related to more common stones and metals in nature, so the physical relationship between glass and the lower value material faience (in terms of their raw ingredients) was not exceptional in this context, though it is further notable that not all of the materials used in the production of the two were necessarily from the same sources (see Paynter and Tite 2001, 246). It might be argued that, as well as being thought of as separate categories of material, glass, metal and stone were also conceptually linked by the properties noted above. Thus it is possible to suggest that glass was seen as a form of stone, but that this does not affect the perception of glass as a material in its own right.

To return to the subject of imitation, a comment should be made on the similarities between glass and stone vessel forms. If glass was seen as a form of stone, the much commented upon (see for example Nicholson 2007, 6; Shortland 2001, 214; Keller 1983, 21) similarity of form (exaggeration aside) between glass and stone vessels is in any case somewhat obsolete in addressing questions of imitation and value. But it should also be noted that this degree of similarity in vessel form is not unique to the relationship between glass and stone, nor do we always see a 'downward' process of transmission, with lower value materials being used to imitate forms first created in higher value materials. Examples of this include fish-shaped spouted flasks thought to be based on ceramic prototypes imported from the Levant (see Lilyquist 2005, 65); certain forms of vessel, such as the ovoid bodied flask, which are also encountered in ceramic forms (see Cooney 1976, 152); and the palm column form, as noted in Chapter 2, which has known parallels in wood.

Can We Argue for a Hierarchy of Glass Colours?

It has been suggested here that not only were different glass colorants obtained from a variety of sources but that even the production of various colours of glass sharing related colorants and opacifiers (in particular those coloured and opacified with antimony) may have involved very different processes, discussed further below, and that certain of these colours of glass were more highly prized than others. Yet it has also been suggested that glass formed a distinct category of material in its own right.

[74] In a linguistic example, Robson (2001, 40) notes that the Akkadian word *abnu* is usually translated as 'stone' but can refer to a range of things including ores and gems, large fruit seeds, hailstones, metal, glass and metrological weights made from any material, though she then argues that glass was an imitation of stone on the basis of its description as *abnu* or *aban kûri* (stone from the kiln).

Two questions thus arise: can we reasonably argue for a hierarchy of colours in glass? If we can, what are the implications of this, especially in terms of the categorisation of glass as a material? I suggest that there are two ways of approaching these questions which, although their answers may at first seem contradictory, can be incorporated into a wider framework for understanding the perception of glass in the Late Bronze Age.

Firstly, in terms of colour it should be noted that despite evidence that glass was first described by colour reference to precious stone in the textual sources, the application of the adjunct 'from the kiln' or similar[75] to these meant that the man-made or at least man-manipulated property of glass lent it a unified categorisation which was conceptually distinct from colour. It should also be noted that various colours of glass were combined in the same finished items, and applied (trailed) contrasting colours were often marvered onto a base colour (or would sink in due to surface tension), removing both the clear distinction between the composite colours either by description or by physical action: in contrast, for example, to a composite inlay where the distinction between areas of different colour and / or material is preserved.

On the other hand, I have suggested that cobalt-blue glass in particular, and perhaps also white, yellow, and red glass, held special associations – symbolic, royal and of restricted or limited access (exoticism, it is suggested, is less easy to define) – which increased their desirability and status over that of, for example, copper-blue or green glass.

Certainly the deliberate control over cobalt in particular suggests that colour was a factor in value and royal association (see below). The particular blues produced by using cobalt in various contexts (glass colouring and pottery painting) served as a signifier of royal control over resources, something reinforced by its symbolic links. But if cobalt blue glass was more desirable than other shades, why do we not see a more marked archaeological or linguistic distinction between objects produced in dark blue and those produced in other colours? And how do white, yellow, red and other colours of glass fit into the picture?

In fact, the most noticeable variation in glass colour is visible diachronically: the initial increase in the production and use of cobalt blue glass; the exclusive production of red glass at Qantir; and the later increase in production of green glasses, coupled with a slight decrease in the quantity of opacified glass from the mid-14th century on (see Nolte 1968). Of course, a decline in the more complex processes involved in opacifying glass and the production of weaker, perhaps less desirable colours such as translucent greens (see below) may suggest a lowering of the status of glass as a whole. But the increase and

[75] Such as the use of the terms *ehlipakku* or *mekku*-stone, which – if they do refer to glass – suggest a unified category for it.

continued interest in the manufacture of cobalt blue and opaque red glass in particular, not to mention the continued use of opaque white and yellow as the primary colours for trailed-on decoration suggests that the colour palette merely widened during the XVIII and XIX Dynasties. Although there may have been some hierarchy of colour *within* glass, the material as a whole retained a broad value in its own right, exemplified in the preference for polychromy.

I thus suggest that, as with the established production of complicated composite objects and the increased use of polychromy in various aspects of design in New Kingdom Egypt (noted in Chapter 4), variety was also preferred in glass. Although certain colours served as markers of status and control, the greatest marker of such was the incorporation of a wide variety of colours, demonstrating control over all resources whether from near or distant lands. Thus a hierarchy of colour existed, but it seems not to have extended the boundaries of the material: the creation of cobalt blue glass, the use of rarer colours and the broad range of hues witnessed in the assemblage all added to the value of glass: value by association, perhaps, for copper-blue or green, but this was rarely found in finished items without connection to other, perhaps more expensive colours.

Manufacturing and Complexity

It has been suggested in Chapter 6 that the raw material acquisition and production processes for antimonate opacified glasses may be rather more complex than has previously been assumed. Although only four samples were analysed with ToF-SIMS, the results were largely consistent with previous analysis of trace and minor elements within antimonate opacified glasses: a key distinction in the present study is that the specific location and co-location of various species within inclusions and matrices can be distinguished. It is thus suggested that the results may be taken, at least for the moment, as representative of other antimonate opacified glasses.

With this assumption in mind, a number of possibilities are suggested for the acquisition of raw ingredients and the subsequent manufacturing processes for lead antimonate opacified glasses:

- A lead antimonate source, such as the mineral bindheimite, was directly added to a preformed glass in order to form lead antimonate yellow, accounting for the co-location of antimony, lead and bismuth within the inclusions. Associated species of zinc and sulphur were present as impurities within this source.
- Antimony was first prepared by sintering together with an (unknown) source of lead which contained the associated impurities of bismuth, sulphur and zinc (though some sulphur may also have been present within the antimony source), resulting in the formation of crystals of lead antimonate with the associated impurities.

- Bindheimite or an unknown mineral containing antimony, lead and bismuth was sintered together with another source of lead, possibly from Gebel Zeit.

Although it cannot be definitively stated which of the above procedures was undertaken, it should be noted that the third option is closest to the data obtained so far, both in the present study and in published material. Previous studies have revealed that isotope signatures for yellow opaque glasses are not entirely consistent with the known fields for lead ores within Egypt nor, perhaps more significantly, with those for other Egyptian materials made using lead (Shortland 2006). It is thus possible that another source of lead with a similar geological age was used, and other lead ores on the Red Sea coast may be contenders for this[76]. It is equally possible, however, that the lead isotope signatures are the result of combining lead from Gebel Zeit or a related ore with lower quantities from another source, primarily included as the source of antimony, the lead content of which was responsible for slight 'shifting' of the field by comparison with other objects. The excess lead found in the yellow opaque glasses from Amarna (noted in the EPMA results in Chapter 5) supports this hypothesis. Similarly, the co-location of zinc and sulphur, detected by ToF-SIMS (particularly clear for Th153, the yellow opaque glass from Mycenaean Thebes) does suggest the presence of spharelite (ZnS) or similar, which has already been suggested to be associated with the use of lead from Gebel Zeit (Shortland 2002, 254).

The presence of bismuth in the inclusions of the lead antimonate, but not the calcium antimonate opacified samples may indicate that different antimony sources were used for both, though it should be borne in mind that the primary origin of Th267 (white opaque glass from Mycenaean Thebes) may have been Mesopotamia rather than Egypt, and that Brak12 (turquoise opaque glass from Tell Brak), given its Mesopotamian provenance, may also have been the result of different raw ingredient use and manufacturing technology. On the other hand, sources of antimony are rather rare, and it is perfectly feasible that Egyptian and Mesopotamian glass production used the same ones, particularly given the possible complexity involved in their preparation and application as a glass colorant. In any case, the ToF-SIMS evidence that arsenic was not associated with the opacifying inclusions of the yellow opaque samples suggests that the relative concentration of this element should no longer be used to argue for a common source of antimony in both types of glass, and it thus remains unclear whether the same source of antimony was used in the production of lead and calcium antimonate opacified glasses.

Whichever scenario is closest to the manufacturing processes employed for these glasses, however, it should be noted that the acquisition of materials and their processing seem to have been markedly complex, involving – particularly for the yellow opaque glasses – the

[76] The lead ores on the Egyptian Red Sea coast are compositionally rather variable, as noted by Brill et al. (1973, 19; see also Castel et al. 1988).

combination of a number of materials or, at the least, the acquisition of imported mineral colorant-opacifiers.

Evidence for recycling to form green glass, presented in Chapter 5, is discussed in more detail below. It should be noted in the present context, however, that whichever scenario is accepted as explaining the compositional evidence – that green glass was made through recycling or that it was made through the addition of a complex preparation of materials to glass – it implies a marked degree of complexity in the production of various different colours of glass. The 'easiest' options from our perspective, with a scientific understanding of the chemistry of various ingredients and their effects, do not appear to have been taken.

Acquisition, Mystification and Transformation: material expressions of power

This complexity of production, at least in terms of coloration, should not be entirely surprising (even if not entirely expected) as previous work has illustrated the prominence of both conservatism and ritual – which do not tend to favour the simplest / most efficient approaches – in ancient or traditional technology (see Budd and Taylor 1995; Hosler 1994) and in glass production in particular (see Miller 2007, 134; Sode and Kock 2001; Moorey 2001, 2). To some extent, conservatism and ritual in production may be accounted for (if not consciously) by the desire to maintain a high chance of success in pyrotechnological processes, but it should also be noted that modern concepts of efficiency cannot be applied wholesale to LBA Egypt (see, for example, Kemp 1989, 291).

Nonetheless, differences in production processes between various colours of glass are significant. Equally, these differences appear to relate primarily to the colouring / opacification stages of manufacture. If we accept arguments that some, or most LBA Egyptian glass was created in a two-stage production process, as discussed in Chapter 5, we might envisage this complexity as relating primarily to the preparation and addition of colorants and colorant-opacifiers. The chemical evidence certainly supports this view, given the apparent differences between various colours of glass not only in terms of composition but in terms of the formation of opacifying inclusions as well.

It is thus suggested that the complexity of glass production – and coloration / opacification in particular – also served to maintain the high status of glass and its royal connections. Furthermore, access to the materials required for certain colorants must have been limited. In addition to the acquisition of cobalt (and its royal connections) discussed in Chapter 4, it should be noted that the importation of antimony, possibly from two separate sources (discussed in Chapter 6 and above), and the need to obtain lead either through expeditions

(to the Red Sea coast) or through long-distance trade illustrate the effort which must have gone into obtaining the colorants required for glass production.

As noted by Carter (1994, 138) technology can be manipulated and controlled by a number of factors: restricted access is certainly one of these, but control can also be achieved where the context of production is hidden, or the processes involved are so complex as to mystify those who witness them. With reference to the first point, the possibility that primary production and colouring constituted two separate stages certainly provides an opening for the idea of a hidden context of production (in this instance, presumably away from the main areas of craft working). But even if primary glass production were situated away from other craft sites, the essential stage of colouring of glass in crucibles – which seems to have occurred in the craft areas of palatial settlements – would have been witnessed by a broader range of people. This being so, the addition of difficult to acquire ingredients, or complex preparations for the purposes of colouring and opacification, would have served to mystify witnesses, and may even have been seen as an essential part of a performative act, possibly enhanced – given Shortland's (2007) contention that glass makers may have had temple associations – by a religious dimension. An essential part of this may have been the transformative aspects of glass production or perhaps more specifically colouring, in particular for those ingredients which imparted to the glass a different colour than the one they possessed in their raw state. These arguments also concur with the suggestion made in Chapter 4 that the primary means of maintaining the value of glass at this time was the skill involved in its production technology[77].

The associations between power and the colour of glass, however, seem to have extended beyond the context of production. Links between colour as a visual attribute and concepts of material provenance are noted in Chapter 3, and evidence for the use of cobalt in the colouring of other artefacts associated with palace sites such as Malkata and Amarna (discussed in Chapter 4) suggests that in this case, the 'provenance' which glass indicated through its colour was that of its manufacturing location, and by association, the powers residing there. The production of red glass at Qantir may also have served to 'proclaim' the royal status of the material. In this instance, the value of the colour was perhaps more closely related to the transformation of the materials rather than the difficulty of acquisition (copper being relatively easy to acquire, at least in the small quantities required for glass production). Thus the acquisition of a range of colorants, their

[77] A comparison might be made here between the role and perception of LBA glass and those of the *tumbaga* metals of the pre-Hispanic Andean Incas: as noted by Lechtman (1984), the complexity of production involved in creating copper alloys which contained either silver or gold increased the value of the material itself, but this complexity was also justified by the resulting colour of the alloy (which, she argues, was prized *over* that of pure gold or silver). Furthermore, the surface colour reflected the internal composition: alloys were created through a complex process of electrochemical deposition, rather than more simple and economic means of gold plating.

transformation, and the transformation even of more readily available colorants such as copper, may be seen to have materially communicated the royal and created status of the resultant glass. The prime signifier of this status was colour.

One further point can be made with reference to what may seem – at first sight – an unnecessary complexity of production: an equal level of complexity is suggested by the Mesopotamian 'glassmaking' texts (see Shortland 2007 for a detailed consideration of these with relation to glass). Even if the texts do not refer to the production of glass itself, and allowing for their removal in space and time from LBA Egyptian glass making, they illustrate that complex, elaborate production procedures were valued enough in the making of coloured materials to be recorded and copied by subsequent generations.

Recycling, Re-melting and Re-use

It has been suggested in Chapter 5 that a limited amount of recycling may have been practised in LBA Egyptian glass production. The 'recycling' referred to is the re-melting and working of finished items of glass only, as re-melting of 'raw' glass (ingots, lumps or canes) must be considered the usual practise for working glass. It must thus be stated at the outset that the recycling of monochrome glass objects made in a single technological tradition within Egypt is analytically undetectable, as discussed further below. Chemical analysis, however, does not deal in invisible practises, and the evidence which has been discussed at length in Chapter 5 is based upon the consistency of the ratio of lead to antimony in samples of green glass. The ratio in which these are present is consistent with that which might be expected to occur from the melting down of preformed polychrome glass vessels (based on the standard colour repertoire of the time, discussed in Chapter 4). As noted in Chapter 3, it is already understood that a combination of lead, antimony and copper can result in a green shade of glass, so the re-melting of preformed glass vessels containing these ingredients would tend to result in green glasses.

Of course, precise calculation of the proportional relationship between applied decoration and the 'base' colours present in finished items is difficult, but it should be noted that vessels were often very thin walled (see Keller 1983, 22), so that the applied colours may have contributed a fair amount to the mix on re-melting. The volume of 'base' glass in beads and other small items is variable, but significantly, the ratio of applied colour on these is similar to that of vessels. Indeed, some variability in the absolute concentration of lead and antimony was noted in the opaque green glasses analysed here, and those which have been classified as 'semi-translucent' have a lower concentration of lead and antimony still. It might thus be argued that differences in the colour proportions of those glasses available for recycling led to a certain degree of unpredictability and variability in the shade and colour (as well as the degree of translucency) produced, and the chemical evidence reflects this.

To return to the issue of 'invisible' recycling, it has been suggested in Chapter 4 that the consistency of glass and its potential for re-melting / hot-working were factors in its perception as a high value product. 'Recycling' (re-use and re-working) of precious stones is thought to have occurred fairly widely during the Late Bronze Age (see Moorey 1994, 86 - 91) and it is thus likely that monochrome glasses were treated in a similar way on occasion, perhaps with the re-use or cold-working of glass inlay. Considering that lumps or ingots of glass – and probably also glass canes – were transported and / or traded for re-melting, it is equally possible that two separate pieces of the same colour of monochrome glass could have been melted together in glass workshops for the creation of finished vessels, where glass would in any case need to be heated in order to manipulate it into form. This may not have been possible for all colours, however: the evidence for low temperature mixing of the colorant-opacifier in the production of yellow glass discussed in Chapters 5 and 6, for example, suggests that complete re-melting of yellow opaque glass may not have been practised due to its negative effects on the colour (causing a 'muddier' yellow). In any case, it is apparent that some forms of such re-melting and re-use of glass made with similar raw ingredients and manufacturing processes *could* have been practised.

The absence of evidence for the *large scale* practise of recycling of finished items, however, may in this case be taken to be a fairly good indication of evidence of absence. As some of the earliest glass in Egypt was imported, for example, we might expect that the practise of widespread recycling would 'blur' the distinction between Egyptian and Mesopotamian isotopic signatures, but as noted in Chapter 5 (see also Henderson et al. 2010), this has not yet found to be the case.

Of course, it might be argued that – as noted above with reference to the complexity of production – some preparation of lead and antimony was created for the production of green glass, the composition of which (and, by implication, perhaps also the provenance of the raw ingredients) was different to that used in the production of either white or yellow opaque glasses (given that it appears to be an intermediate between the two). But as noted in Chapter 5, the BSE images for the green glasses analysed in this study reveal small, fairly well dispersed inclusions, more consistent with precipitation from a melt. Certainly this was not the practise with the production of the yellow lead antimonate opacified glasses, so the addition of a preparation of lead antimonate seems less likely. Furthermore, it is suggested below that the recycling of objects to form green glass is in fact in keeping with the picture of glass production and perception presented above.

One technological reason to avoid recycling is a lack of control over colour. The survey of colour use in Egyptian vessels and small items presented in Chapter 4, however, illustrates that the primary base and applied colours in glass add up to the right combination to

produce the chemical signal of the opaque and semi-translucent green glass discussed in Chapter 5. Thus recycling of polychrome objects could *only* consistently result in green glass, though it should be emphasised that this does not preclude the possible addition of small amounts of glass cullet to aid formation of raw ingredients into a primary glass.

I do not suggest, *contra* Sherratt (2008, 217), that polychrome glass vessels provided a deliberate means to restrict access to glass, through the prevention of recycling (though it should be noted that Sherratt refers specifically to Mesopotamian, not Egyptian glass). The relatively restricted circulation of glass and the technological requirements of working it would surely limit the potential for 'lower level' recycling for most of the period in question. The evidence from Lisht (see Chapter 2) may indicate that this practise was beginning towards the end of the second millennium, however, and it is possible that the large scale production of red glass at Qantir reflects a deliberate emphasis on the royal associations of glass: the technological challenges of creating red glass (discussed in Chapter 3) preclude its re-melting by unskilled parties.

It should also be noted that green was not among the most popularly used colours of glass for prestigious items, as illustrated in Chapter 4. The symbolic associations of green (fertility and in some contexts eternal life) may suggest that this was not related to a particular distaste for green itself where it is considered – if indeed it may be considered – as a hue divorced from material. Yet colour categorisation, it has been argued, must allow for a measure of complexity and context of use. Thus it is also possible that the importance of the related concepts of colour, durability and consistency which (it is argued here) were so central to the value and perception of glass were negatively influenced for green by other factors symbolically associated with green stones or metals, such as the lack of durability of greenish turquoise, or even – as suggested by Peters (2008) in the context of Minoan glass production – the green colour of corrosion products of copper and bronze.

On the other hand, it is possible that the lesser status of green within the 'hierarchy' of glass was a direct result of its manufacturing processes and its relationship to other colours of glass. For example, a translucent green shade commonly results from the production of 'naturally' coloured (uncoloured) glass (as noted in Chapter 3). Given the evidence (based on contexts of use: see Chapter 4) that colourless glass was prized, a greenish tinge is unlikely to have been particularly welcomed. Similarly, if 'naturally' coloured glass was produced in the first stage of the 'two-stage' model for glass production, glass with a similar greenish tinge will have been understood as a primary product, not a finished material. Finally, the production of blue glass using copper may on occasion have yielded green by accident, and green crusts could also form unintentionally over red opaque glasses. In any case, it has been argued that early glass making focused on the production

of strong, saturated colours, and 'weaker' shades such as translucent green may not have been quite as desirable.

Opaque green glass is more difficult to place, but it may have been conceptually linked with the translucent version of the same colour. The evidence presented in Chapter 5 certainly suggests that there was no marked distinction between the production of 'semi-translucent' and opaque greens in terms of their manufacture (the key difference being the quantity of lead antimonate present). Additionally, though re-melting, or even recycling of monochrome material is not suggested to have held negative connotations, the recycling of polychrome vessels in the production of green glass does not involve the important stage of control / creation through the acquisition or transformation of prepared materials or raw ingredients, but reduces transformation to what might be termed the adaptation, or even deterioration, of colours of pre-formed glass[78].

Finally, it should be noted that the large volume of glass ingots which appear to have been produced in the Late Bronze Age (as found at Ulu Burun, or depicted in the *Annales* of Tuthmosis III at Karnak) fall short of the limited amount of finished glass objects known from the period by a long way (as commented upon by Nicholson 2007, 4). This may in part be accounted for by the practise of recycling and the addition of cullet to glass melts. Re-melting of monochrome glass, in particular to form smaller items such as beads (which require less control over the material than vessels), should not be ruled out either, as noted above. It is probable that much of this recycling occurred towards the end of the period under discussion, or even afterwards: the evidence of lower quality glass working from Lisht outlined in Chapter 2, or from the burial of Nesikhons discussed in Chapter 4, may relate to this. On the other hand, Shortland (2007) has noted that the lack of glass finds from settlement areas in Amarna, which he relates to the value of the material (as, unlike faience, it was not left behind on abandonment of the site). But it is also possible that this value, manifested in the lack of discarded fragments from glass items (though the discovery of glass vessel fragments from Petrie's investigation of the Palace Dumps provides a notable exception), meant that even broken glass items could be reused in some form.

[78] An interesting point for future consideration is whether this re-melting was practised by primary glass makers or by glass workers, who were used to re-melting raw glass. The latter suggestion is intriguing indeed, as it might be expected to dilute the power of those involved in primary glass production. In this case, the limitation of this practice to green glass may be further supported, given its seemingly lower status by comparison with other glass colours. Indeed, the difficulties of producing more valued colours of glass through the practice of recycling preformed glass objects would serve to reinforce the status and power of those who were involved in primary glass production and the creation of other colours of glass.

Addressing the Material Record

In Chapter 1 it is stated that a secondary aim of the present study is to address broader questions about materiality based approaches in general, and the study of colour in particular. It is hoped that the combination of approaches discussed above has illustrated the increased potential of materiality in reconciling apparently disparate strands of evidence, through focus on a narrow range of interrelated questions. The place of colour within this approach is now considered in more detail.

The study of colour has recently undergone something of a renaissance in archaeological thought, as a quick glance at the bibliography of the present work will show. Nonetheless, it is often considered almost as a separate category of analysis, and – in archaeometric approaches in particular – seen as a sort of 'end in itself', with a focus on identifying the chemistry of certain pigments but not on explaining the significance of the colour in these. Linguistic studies into colour are, perhaps unsurprisingly, more developed. With some very notable exceptions (see Boriç 2002; Cooney 2002; Hosler 1994; Bradley and Edmonds 1993), much colour research focuses primarily on pigments and dyes; that is, applied colour. But colour is an essential material property, and as a primary means by which materials are identified and categorised, must be addressed on a broader scale.

Figure 7.2 is thus included to provide an illustration of the arguments offered here for the interplay between colour and other properties in the perception of materials, with a focus on colour as an intrinsic material property rather than something which is applied or incidental. Colour (defined on the basis of brilliance and saturation as well as hue) is placed along with other material properties, but may also be seen as a marker of these. The perception and classification of colour is related to both the specific material considered and to external referents. In particular, colour as a marker of exoticism or rarity is considered as a factor in this, and the paths of reference are not unidirectional. The combination of these factors is central to the perception and classification of materials.

It is apparent that the above factors are complex and addressing them requires a broad consideration of the context into which colour must be placed. Systems of reference are neither universal nor immune to alteration, and the full range of factors involved in the classification and use of materials must not only be considered, but be considered as subject to change. The introduction of a new material must at first fit into pre-existing categories, but it may also influence and affect these. As noted in Chapter 3, acknowledging the differences between the specific contexts in which colour is studied is more important than the adoption of a single framework for analysis, but it is suggested that only by recourse to the full range of factors associated with colour and material properties may certain elements be justifiably excluded from consideration.

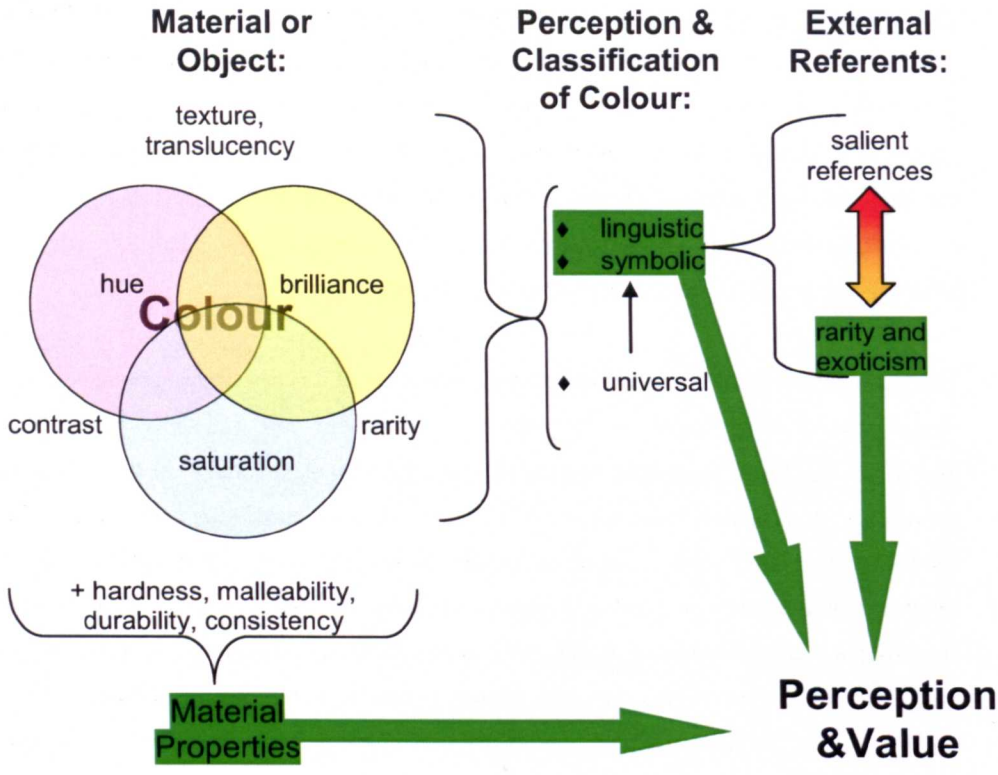

Figure 7.2 Schematic Summary of the Relationship Between Colour and Other Material Properties in Perception and Value.

Conclusions

In summary, it is noted that although there was an increase in the scale of glass production during the XVIII and XIX Dynasties, it remained a high status material in Egypt. I suggest the following reasons for this:

- Glass was valued on the basis of its specific material properties. This being the case, 'raw' glass can be argued to have held intrinsic (prime) value, and was seen as a material in its own right, coincident with the categories of metal and stone which were also valued on this basis.
- Glassmaking involved a high degree of specialisation. The required level of specialisation was increased by the complexity involved in producing various different colours of glass.
- The transformative aspects of glass production, and the complexity of preparation of various raw materials as colorants and / or opacifiers, may also have increased the mystery surrounding its production, and served to reinforce the specialism and skill of the individuals involved in this.
- The need to acquire specific, sometimes difficult to access raw ingredients for glass colouring meant that glass production was closely linked to central control and royal power: in this instance, the visually proclaimed 'provenance' of the glass was related to the location of its colouring.

- Glass production is further restricted by the colour requirements of finished objects. As well as deliberate strategies of elite control over access to raw materials required for the primary production of certain colours of glass, the polychrome nature of most finished objects demands access to a range of pre-made, coloured glasses for those involved in glass working.

All of the above factors can be related to elite control over the industry, with differing degrees of intention. A key point is that the colours of glass seem to play the central role in the continuation of its high value and royal associations.

Where it was understood that glass was an artificial (created) material this did not necessarily lessen its value or symbolic associations. The description of glass as 'royal' in the *Annales* at Karnak provides an early example of how its difference from the natural stone might have been seen as a positive attribute of the material. It has been argued elsewhere (Sherratt 2008, 214; Shortland 2007, 271) that LBA glass production is something akin to medieval concepts of alchemy, as a valued material is created through transformative processes from 'base' raw ingredients. But this is not enough to maintain long term value or strategies of control.

In purely economic terms, the relative 'expected' value of glass *ought* to decline (see Miller 2007, 212 - 217) once it is understood as a man-made (and therefore predictable in production) material whose supply of basic raw ingredients (soda, silica and lime) is relatively constant, being dependent on plant ash and silica that, when fused, begin to behave in a 'predictable' way. Certainly the increasing abundance of glass production throughout the Late Bronze Age suggests that its initial status as a rare or exotic material cannot have been enough to maintain its value. But the elaboration and complexity of glass colouring, coupled with the difficulty of procurement of those raw materials required to produce specific colours, allowed control over its status and distribution to remain firmly in the hands of the central powers under which it was produced.

Furthermore, transformation should perhaps be considered less in terms of the change from 'base' ingredients to glass (which in any case, following the two-stage production model, may have been located far from other craft processes), than in the spectacular transformation of colorants into specific colours of glass. This process of coloration was quite unlike others in that the final product was immutable; a 'raw' material with intrinsic value which could be transported in ingot form, thus making it apparent – even to those with no first hand knowledge of its production processes – that it could be re-worked without losing those properties which rendered it valuable.

Egyptian concepts of the mineral universe, particularly the relationship between precious stones – recognised by their colours – and the creative powers of the gods, may also hint at the proper place for glass: it was created by the central powers of government and temple and as such was a manifestation of their divine links. Acquisition and combination of numerous colours served to further enhance the impression of control over resources; and deliberate, ordered designs in finished vessels and other items acted as signals for command over the natural world.

Considering the evidence that colour, in Egyptian thought at least, was seen as one of the essential properties of a thing, in particular where it was not simply a surface feature, it is hardly surprising that glass could be described in terms of precious stones, both as a means of expressing the particular colour of the material and as a means of conceptually linking a certain colour of glass with the precious stones themselves. Both are valid interpretations, and both appear to relate to the way in which glass, colour and material properties were understood at the time. Precious stones were, after all, used as referents for a wide range of materials. Indeed we do ourselves a disservice when we divorce colour from hue and attempt to fit linguistic and material evidence into a series of pre-formed categories. The reality is that the understanding and associations of colour were as wide and varied as they are today, and that the complexity of symbolism and the relationship between materials – far from being an annoying confusion to be disentangled by modern scholarship – was part of an intricate and rich way of viewing the world. Precious stones were related to the heavens, created by the gods. Glass creation was in the hands of the central royal, and possibly religious, authorities and these were able to emphasise their links to divinity and divine power by manipulation of the material world. Thus if glass can ever be described as an imitation, we might do better to describe the act of making it – rather than the material itself – as the imitation, or realisation, of ultimate power rooted in the ability to create.

Suggestions for Future Work

The present study has raised a number of questions which would benefit from further investigation, in particular in terms of archaeometric research. These have already been touched upon in the main body of the text, and are summarised here as follows:

1. Given the exploratory nature of the ToF-SIMS research presented in this study, a number of suggestions for methodology and the optimisation of the experimental parameters have already been made in Chapter 6. Due to the enormous scope of the technique, it could be used to address almost any question regarding the composition and manufacturing technology of opaque LBA glass. It is suggested, however, that the most important future direction for the use of ToF-SIMS is the analysis of a broader sample set, allowing comparisons between different colours of glass from various regional locations. A powerful advantage over other techniques here is the post-analytical raw data potential: analytical data can be retrieved, and spectra or images reconstructed from these. As the full mass spectrum is calculated during analysis, it is not necessary to exclude the collection of those signals which are less relevant at the time of analysis. Thus it is suggested that, even if a large scale ToF-SIMS study of ancient glass is not conducted, the data from previous programmes of analysis (changes in experimental parameters and conditions considered) can be broadly compared, and – perhaps more importantly – new questions can be asked of old data. In particular, the following issues should be pursued: the development of quantitative methods of analysis and, using these, the investigation of isotope signatures. Both would be of significance in further discerning the possible origins of particular raw materials associated with inclusions and matrices. The analysis of opaque glasses produced using different processes, times and temperatures might also be useful, in order to establish the precise interaction between inclusions and matrix, and to develop an understanding of the relationship between opacification and temperature at the microscopic level.
2. The possible evidence for the practice of recycling in LBA glass should be more fully explored, despite the difficulties of doing so. In particular, the possible use of glass cullet as an explanation for low levels of various elements associated with colorants in LBA glasses needs to be investigated. Trace element analysis using LA-ICP-MS has already proven a powerful tool, but studies using this have largely focused on issues of provenance, so that some colours of glass are represented by only one or two samples (see Walton et al. 2009). Shortland et al. (2007) investigated issues of production technology, but the particular questions addressed meant that only blue and colourless glass was sampled and analysed.
3. ToF-SIMS investigation could also provide powerful results in this area. In particular, the levels of lead and antimony in the matrix and inclusions should be compared, and the composition (and internal distribution) of inclusions in opaque

green glasses should be compared with those in opaque yellow, in order to examine the suggestion presented here that opacifiers in some green glasses precipitated out of the melt and were not added in the same form as those found in yellow opaque glasses. The association of bismuth, zinc, arsenic and sulphur, related to the source and preparation of antimonate inclusions in yellow opaque glasses could also be investigated.

4. Finally, the investigation of long-term changes has been somewhat marginalised in recent years. The study of materials and the factors involved in their perception and value, however, would certainly benefit from such an approach (providing that a tight focus is maintained). The EPMA results for 1st millennium samples given in the present study already illustrate that much remains to be done in this area if we are to fully understand the change in glass production over time. Of particular interest is the investigation of glass from compositional categories for which the parameters are still being developed. For example, EPMA revealed a distinct compositional group of samples from Ur, and the only parallels for this so far known have been later glass from Afghanistan. The long-distance travel of glass is particularly visible where such categories are discernable, and the possible LMHK signature of another sample from Ur may illustrate this. It has also been noted that the Italian samples from the early 1st millennium were probably made through the importation of raw materials from different sources, and it is thus apparent that the broad scale of considerations must also be applied in the geographical context. The early 1st millennium is the period when glass production spreads outwards from its core centres of the Late Bronze Age, but it is also a period in which glass is found in lesser quantities, and has been less frequently studied: its fuller comprehension is thus vital in its own right. But focus on these issues would also provide a broader context for understanding LBA glass production, in terms of 'where it went', and later 1st millennium B.C. glass production, in terms of 'where it came from'. Such issues are central to developing an understanding of human interaction with materials, and the shifting categories by which these are perceived.

Bibliography

Andrescu-Treadgold, I. and Henderson, Julian 2008 Glass mosaics on the west wall of Torcello's Basilica. *Arte Medievale* V: 87 – 141.

Andrews, Carol 1994 *Amulets of Ancient Egypt*. London: British Museum Press.

Angelini, Ivana, Artioli, Gilberto, Bellintani, Paol, Diella, Valeria, Gemmi, Mauro, Polla, Angela and Rossi, Antonella 2004 Chemical analyses of Bronze Age glasses from Frattesina di Rovigo, northern Italy. *Journal of Archaeological Science* 31: 1175 – 1184.

Archi, Alfonso (ed.) 1984 *Circulation of Goods in Non-Palatial Contexts in the Ancient Near East*. Rome: Dell'Ateneo.

Archi, Alfonso 1984 Anatolia in the Second Millennium B.C. In Archi, Alfonso (ed.) 1984 *Circulation of Goods in Non-Palatial Contexts in the Ancient Near East*. Rome: Dell'Ateneo. pp. 195 – 206.

Arletti, R., Dalconi, M. C., Quartieri, S., Triscari, M and Vezzalini, G. 2006 Roman coloured and opaque glass: a chemical and spectroscopic study. *Applied Physics A; Materials Science & Processing* 83: 239 – 245.

Arletti, R., Maiorano, C., Ferrari, D., Vezzalini, G. and Quartieri, S. 2009 The first archaeometric data on polychrome Iron Age glass from sites located in northern Italy. *Journal of Archaeological Science* 37 (4): 703 – 712.

Askeland, D. R. 1998 *The Science and Engineering of Materials* 3rd S. I. Edition. London: Nelson Thornes Ltd.

Aufrère, Sydney H. 2001 The Egyptian temple: substitute for the mineral universe. In W. V. Davies *Colour and Painting in Ancient Egypt*. London: The British Museum Press. pp. 158 – 163.

Averbeck, R., Chavalas, M. and Weisberg, D. (eds.) 2003 *Life and Culture in the Ancient Near East*. Bethesda, MD: CDL.

Avruch, Kevin 2000 Reciprocity, equality, and status-anxiety in the Amarna letters. In Raymond Cohen and Raymond Westbrook (eds.) *Amarna Diplomacy: the beginnings of international relations*. Baltimore and London: The John Hopkins University Press. pp. 154 – 164.

Baines, John 1985 Colour terminology and colour classification: ancient Egyptian colour terminology and polychromy. *American Anthropologist* 87 (2): 282 – 297.

Baines, John and Málek, Jaromír 1984 *Atlas of Ancient Egypt*. Oxford: Equinox.

Ballard, L. 1994 The centre cannot hold: trade networks and sacred geography in the Papua New Guinea highlands. *Archaeology in Oceania* 29 (3): 130 – 148.

Bamford, C. R. 1982 Optical properties of flat glass. *Journal of Non-crystalline solids* 47 (1): 1 – 20.

Barag, D. 1962 Mesopotamian glass vessels of the second millennium BC. *Journal of Glass Studies* 4.

Barag, D. 1970 Mesopotamian core-formed vessels. In A. Leo Oppenheim, Robert H. Brill, Axel Von Saldern and Dan Barag *Glass and Glassmaking in Ancient Mesopotamia: an edition of the Cuneiform texts which contain instructions for glassmakers with a*

catalogue of surviving objects. The Corning Museum of Glass Monographs Volume III. Corning: The Corning Museum of Glass Press. pp. 131 - 197.

Barag, D. 1985 *Catalogue of Western Asiatic Glass in the British Museum*. Volume I. London: British Museum Publications Ltd.

Barber, D. J. and Freestone, I.C. 1990 An investigation of the origin of the colour of the Lycurgus Cup by analytical Transmission Electron Microscopy. *Archaeometry* 32: 33 – 45.

Barkoudah, Youssef and Henderson, Julian 2006 Plant ashes from Syria and the manufacture of ancient glass: ethnographic and scientific aspects. *Journal of Glass Studies* 48: 297 – 321.

Bass, G. F. 1998 Sailing between the Aegean and the Orient in the second millennium BC. In Eric H. Cline and Diane Harris-Cline (eds.) *The Aegean and the Orient in the Second Millennium: proceedings of the 50th Anniversary Symposium, Cincinnati, 18 – 20th April 1997*. Liège: Histoire de l'Art et Archéologie de la Grèce Antique.

Bass, George F., Frey, Donald A. and Pulak, Cemal 1984 A Late Bronze Age shipwreck at Kas, Turkey. *The International Journal of Nautical Archaeology and Underwater Exploration* 13 (4): 271 – 279.

Baxter, M. J. 1992 Statistical analysis of chemical compositional data and the comparison of analyses. *Archaeometry* 34 (2): 267 – 277.

Baxter, M. J. 1995 Standardisation and transformation in Principal Component Analysis, with applications to archaeometry. *Applied Statistics* 44 (4): 513 – 527.

Baxter, M. J., Cool, H. E. M., Heyworth, M. P. and Jackson, C. 1995 Compositional variability in colourless Roman vessel glass. *Archaeometry* 37 (1): 129 – 141.

Baxter, M. J., Cool, H. E. M. and C. M. Jackson 2006 Comparing glass compositional analyses. *Archaeometry* 48 (3): 399 – 414.

The Bead Study Trust 1997 *Catalogue of the Beck Collection, Part 1: Europe*. (contributors are George Boon; Flora Westlake; Peter Francis, Jr.; Julian Henderson and Helen Hughes-Brock). Cambridge: the Bead Study Trust.

Beadnell, H. J. L. 1909 *An Egyptian Oasis, an account of the Kharga Oasis in the Libyan Desert with Specific Reference to its History, Physical Geography and Water Supply*. London: J. Murray.

Beck, Horace C. 1927 Classification and nomenclature of beads and pendants. *Archaeologia* 77: 1 – 76.

Bennet, John 2008 Palace™: speculations on palatial production in Mycenaean Greece with (some) reference to glass. In Caroline M. Jackson and Emma C. Wager (eds.) *Vitreous Materials in the Late Bronze Age Aegean*. Oxford: Oxbow. pp. 151 – 172.

Benninghoven, Alfred 2001 The history of Static SIMS: a personal perspective. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 41 – 72.

Berlin, B. and Kay, P. 1969 *Basic Colour Terms: their universality and evolution*. Berkeley: University of California Press.

Bianchi, Robert Steven 1998 Symbols and meanings. In Florence Dunn Friedman (ed.) *Gifts of the Nile: ancient Egyptian faience*. London: Thames and Hudson. pp. 22 – 32.

Biavati, A. and Verità, M. 1989 The glass from Frattesina, a glassmaking centre in the Late Bronze Age. *Rivista della Stazione Sperimentale del Vetro* 4: 295 – 299.

Biek, Leo and Bayley, Justine 1979 Glass and other vitreous materials. *World Archaeology* 11 (1): 1 – 25.

Bimson, M. and Freestone, I.C. 1983 An analytical study of the relationship between the Portland Vase and some other Roman cameo glasses. *Journal of Glass Studies* 25: 55 – 64.

Bimson, M. and Freestone, I. C. 1988 Some Egyptian glasses dated by royal inscriptions. *Journal of Glass Studies* 30: 1 – 15.

Bimson, M. and Freestone, I. C. (eds.) 1992 *Early Vitreous Materials*. British Museum Occasional Paper 56. London: British Museum Press.

Birch, Samuel 1853 *The Annals of Thothmes the Third as Derived from the Hieroglyphic Inscriptions*. Archaeologia Vol. XXXV.London: J. B. Nichols and Sons.

Blackmann, H. G., H. Everts and C. A. Hope 1980 Cobalt blue pigment on 18th Dynasty Egyptian pottery. *MDIK* 36: 33 – 37.

Bleiberg, Edward 2000 The Economy of Ancient Egypt. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (eds.) *Civilisations of the Ancient Near East*. Volume I. Massachusetts: Hendrickson. pp. 1373 – 1385.

Boivin, N. 2005 Comments I: post-textual archaeology and archaeological science. Comments on A. Jones, 'Archaeometry and materiality: materials-based analysis in theory and practice', *Archaeometry* 46 (3), 327 – 338, 2004, and reply. *Archaeometry* 47 (1): 175 – 207.

Bolton, R. 1978 Black, white and red all over: the riddle of colour term salience. *Ethnology* 17 (3): 287 – 311.

Bongenaar, A. (ed.) 2000 *Interdependency of Institutions and Private Entrepreneurs*. Leiden: Nederlands Historisch-Archaeologisch Instituut te Istanbul.

Boriç, Dusan 2002 Atropism and the temporality of colours: colourful Mesolithic – Neolithic seasons in the Danube Gorges. In Andrew Jones and Gavin MacGregor (eds.) *Colouring the Past: the significance of colour in archaeological research*. Oxford: Berg. pp. 23 – 44.

Boulogne, Stéphanie and Henderson, Julian 2009 Indian glass in the Middle East? Medieval and Ottoman glass bangles from Central Jordan. *Journal of Glass Studies* 51: 53 – 75.

Bradley, R. and Edmonds, M. 1993 *Interpreting the Axe Trade: production and exchange in Neolithic Britain*. Cambridge: Cambridge University Press.

Bray, P. J. and Pollard, A. M. 2005 Comments II: the underpinnings and consequences of the materiality approach. Comments on A. Jones, 'Archaeometry and materiality: materials-based analysis in theory and practice', *Archaeometry* 46 (3), 327 – 338, 2004, and reply. *Archaeometry* 47 (1): 175 – 207.

Briggs, David 2001 Interpretation of spectra. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 447 - 474.

Brill, Robert H. 1963 Ancient glass. *Scientific American*: 120 – 130.

Brill, Robert H. 1969 Lead isotopes in ancient glass. *Annales du 4^e Congrès Internationale des 'Journées Internationales du Verre'*. Liège: Association Internationale pour l'Histoire du Verre. pp. 255 – 261.

Brill, Robert H. 1970 Lead and oxygen isotopes in ancient objects. *Philosophical Transactions of the Royal Society* 269: 143 – 164.

Brill, Robert H. 1971 The chemical interpretation of the texts. In A. Leo Oppenheim, Robert H. Brill, Axel Von Saldern and Dan Barag *Glass and Glassmaking in Ancient Mesopotamia: an edition of the cuneiform texts which contain instructions for glassmakers with a catalogue of surviving objects*. The Corning Museum of Glass Monographs Volume III. Corning: The Corning Museum of Glass Press. pp. 105 – 128.

Brill, Robert H. 1974 Lead isotopes in some ancient Egyptian objects. *Recent Advances in Science and technology of Materials (Cairo Solid State Conference II)*: 9 – 27.

Brill, Robert H. 1989 Thoughts on the glass of central Asia with analyses of some glasses from Afghanistan. *Proceedings of the XV International Congress on Glass, Leningrad, 1989*. Moscow: Rotoprint. pp. 19 – 24.

Brill, Robert H. 1992 Chemical analyses of some glasses from Frattesina. *Journal of Glass Studies* 34: 11 – 22.

Brill, Robert H. 1999a *Chemical Analyses of Early Glasses*. Volume 1: catalogue of samples. New York: The Corning Museum of Glass.

Brill, Robert H. 1999b *Chemical Analyses of Early Glasses*. Volume 2: tables of analyses. New York: The Corning Museum of Glass.

Brill, Robert H. and Cahill, Nicholas D. 1988 A red opaque glass from Sardis and some thoughts on red opaques in general. *Journal of Glass Studies* 30: 16 – 27.

Brill, Robert H., Barnes, I. L. and Adams, B. 1974 Lead isotopes in some ancient Egyptian objects. In A. Bishay (ed.) *Recent Advances in the Science and Technology of Materials*. New York: Plenum Press. pp. 9 – 27.

Brill, Robert H., Shirahata, H., Lilyquist, C. and Vocke, R. D., Jr. 1993 Lead isotope analyses of some objects from Egypt and the Near East. In Lilyquist and Brill 1993 *Studies in Early Egyptian Glass*. New York: The Metropolitan Museum of Art. pp. 59 – 65.

Bryan, Betsy M. 1996 Art, empire and the end of the Late Bronze Age. In Jerrold S. Cooper and Glenn M. Schwartz (eds.) *The Study of the Ancient Near East in the Twenty-First Century*. The William Foxwell Albright Centennial Conference. USA: Eisenbrauns. pp. 33 – 80.

Bryce, T. R. 1998 *The Kingdom of the Hittites*. Oxford: Clarendon.

Bryce, T. R. 2003 *Life and Society in the Hittite World*. Oxford: OUP.

Budd, Paul and Taylor, Timothy 1995 The faerie smith meets the bronze industry: magic versus science in the interpretation of prehistoric metal-making. *World Archaeology* 27 (1): 133 - 143.

Cable, M. and Smedley, J. W. 1987 The replication of an opaque red glass from Nimrud. In Bimson and Freestone (eds.) *Early Vitreous Materials*. British Museum Occasional Paper 56. London: British Museum Press. pp. 151 – 164.

Camagna, S. and Colinart, S. 2003 The Egyptian green pigment: its manufacturing process and links to Egyptian blue. *Archaeometry* 45 (4): 637 – 658.

Caron, Beaudoin and Zoïtopoúlou, Eléni 2008 *Montreal Museum of Fine Arts, Collection of Mediterranean Antiquities. Volume I: the ancient glass*. Leiden: Brill.

Carter, Tristan 1994 Southern Aegean fashion victims: an overlooked aspect of Early Bronze Age burial practices. In Nick Ashton and Andrew David (Eds.) *Stories in Stone*. London: Lithic Studies Society. pp. 127 – 143.

Castel, Georges, Pouit, Georges and Soukiassian, Georges 1988 Les mines de galène pharaoniques du Gebel Zeit (Égypte) dans le Mioncène du rift de la Mer Rouge. *Chron. Rech. Min.* 492: 19 – 32.

Causey, Faye 2004 Amber. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World*. BAR International Series 1267. Oxford: Archaeopress. pp. 74 - 77.

Chapman, John 2002 Colourful prehistories: the problem with the Berlin and Kay colour paradigm. In Andrew Jones and Gavin MacGregor (eds.) *Colouring the Past: the significance of colour in archaeological research*. Oxford: Berg. pp. 45 – 72.

Charleston, R. J. 1963 Glass "cakes" as raw material and articles of commerce. *Journal of Glass Studies* 5: 54 – 67.

Charleston, R. J. 1978 Glass furnaces through the ages. *Journal of Glass Studies* 20: 9 – 34.

Charpin, Dominique 2000 The history of Ancient Mesopotamia: an overview. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 807 - 829.

Charpin, Dominique and Joanes, F. (eds.) 1992 *La circulation des biens, des personnes et des idees dans le Proche-Orient ancien*. Paris: Recherche sur les civilisations.

Chase, W. T. 1971 Egyptian blue as a pigment and ceramic material. In R. H. Brill (ed.) *Science and Archaeology*. Cambridge, Mass.: M.I.T. Press. pp. 80 – 90.

Clarke, Michael 2004 The semantics of the Early Greek word-hoard. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World*. BAR International Series 1267. Oxford: Archaeopress. pp. 131 - 139.

Cline, Eric H. 1994 *Sailing the Wine-Dark Sea: international trade and the Late Bronze Age Aegean*. BAR International Series 591. Oxford: Archaeopress.

Cline, Eric H. 1998 The Amarna Age: western Asia. *American Journal of Archaeology* 102 (3): 644 – 645.

Cohen, Raymond and Westbrook, Raymond (eds.) 2000 *Amarna Diplomacy: the beginnings of international relations*. Baltimore and London: The John Hopkins University Press.

Çolakoğlu, Ali Rıza 2009 Geology and geochemical characteristics of Gevaş listwaenites (Van-Turkey). *Yerbilimleri* 30 (1): 59 – 81.

Colinart, Sylvie 2001 Analysis of iconographic yellow colour in Ancient Egyptian painting. In W. V. Davies (ed.) *Colour and Painting in Ancient Egypt*. London: The British Museum Press.

Conklin, H. C. 1952 Hanunoo colour categories. *South Western Journal of Anthropology* 11 (4): 339 – 344.

Conklin, H. C. 1973 Colour categorisation. Review of Berlin and Kay 1969. *American Anthropology* 75 (4): 931 – 942.

Cooney, Gabriel 2002 So many shades of rock: colour symbolism and Irish stone axeheads. In Andrew Jones and Gavin MacGregor (eds.) *Colouring the Past: the significance of colour in archaeological research*. Oxford: Berg. pp. 93 – 108.

Cooney, John D. 1960 Glass sculpture in Ancient Egypt. *Journal of Glass Studies* 2: 10 – 43.

Cooney, John D. 1976 *Catalogue of Egyptian Antiquities in the British Museum IV: glass*. London: British Museum Publications Ltd.

Costin, C. 1991 Craft specialisation: issues in defining, documenting and explaining the organisation of production. *Archaeological Method and Theory* 3: 1 – 56.

Currie, G. 2004 *Arts and Minds*. Oxford: Clarendon Press.

Deacy, Susan and Villing, Alexandra 2004 Athena blues? Colour and divinity in Ancient Greece. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World*. BAR International Series 1267. Oxford: Archaeopress. pp. 85 – 90.

Degryse, P., Schneider, J., Haack, U., Lauwers, V., Poblome, J., Waelkens, M. and Muchez, Ph. 2006 Evidence for glass 'recycling' using Pb and Sr isotopic ratios and Sr-mixing lines: the case of early Byzantine Sagalassos. *Journal of Archaeological Science* 33: 494 – 501.

Degryse, P. and Schneider, J. 2008 Pliny the Elder and Sr-Nd isotopes: tracing the provenance of raw materials for Roman glass production. *Journal of Archaeological Science* 35: 1993 – 2000.

Degryse, P., Boyce, A., Erb-Satullo, N., Eremin, K., Kirk, S., Scott, R., Shortland, A.J., Schneider, J. and Walton, M. 2010 Isotopic discriminants between Late Bronze Age glasses from Egypt and the Near East. *Archaeometry* 52 (3): 380 – 388.

Dickinson, Oliver 1994 *The Aegean Bronze Age*. Cambridge World Archaeology. Cambridge: Cambridge University Press.

Dik, J., Hermens, E., Peschar, R. and Schenk, H. 2005 Early production recipes for lead antimonite yellow in Italian art. *Archaeometry* 47 (3): 593 – 607.

Dobres, Marcia-Anne and Hoffman, Christopher R. 1994 Social agency and the dynamics of prehistoric technology. *Journal of Archaeological Method and Theory* 1 (3): 211 – 258.

Dornan, Jennifer L. 2002 Agency and archaeology: past, present and future directions. *Journal of Archaeological Method and Theory* 9 (4): 303 – 329.

Drenkhahn, Rosemarie 2000 Artists and artisans in Pharaonic Egypt. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 331 - 343.

Drews, Robert 1993 *The end of the Bronze Age: changes in warfare and the catastrophe ca. 1200 BC*. New Jersey: Princeton University Press.

Duigan, Michael 2004 Colour and the deceptive gift. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World*. BAR International Series 1267. Oxford: Archaeopress. pp. 78 - 84.

Dussart, Odile, Velde, Bruce, Blanc, Pierre-Marie and Sodini, Jean-Pierre 2004 Glass from Qal-at Sem'an (northern Syria): the reworking of glass during the transition from Roman to Islamic compositions. *Journal of Glass Studies* 46: 67 – 83.

Eaverly, Mary Ann 2004 Colours of power: brown men *and* brown women in the art of Akhenaten. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World.* BAR International Series 1267. Oxford: Archaeopress. pp. 53 - 55.

El Goresy, A., Tera, F., Schlick-Nolte, B. and Pernicka, E. 1997 Chemistry and lead isotopic compositions of glass from a Ramesside workshop at Lisht and Egyptian lead ores: a test for a genetic link and for the source of glass. *Proceedings of the 7th Annual Congress of Egyptologists 1997.*

Emberling, G. and McDonald, H. 2002 Recent finds from the northern Mesopotamian city of Tell Brak. *Antiquity* 76: 949 – 950.

Engle, Anita 1973 3000 years of glassmaking on the Phoenician coast. *Readings in Glass History*: 11 – 26.

Eremin, Katherine, Quye, Anita, Edwards, Howell, Jorge Villar, Susana and Manley, Bill 2004 Colours of Ancient Egyptian funerary artefacts in the National Museums of Scotland. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World.* BAR International Series 1267. Oxford: Archaeopress. pp. 1 – 8.

Fitzhugh, Ben 2001 Risk and invention in human technological evolution. *Journal of Anthropological Archaeology* 20 125 – 167.

Forbes, R. J. 1957 *Studies in Ancient Technology*. Volume V. Leiden: E. J. Brill.

Freestone, Ian C. 1991 Looking into glass. In Sheridan Bowman (ed.) *Science and the Past.* London: British Museum Press. pp. 37 – 54.

Freestone, Ian C. 1992 Composition and microstructure of early opaque red glass. In M. Bimson and I. C. Freestone (eds.) *Early Vitreous Materials.* British Museum Occasional Paper no. 56. London: British Museum.

Freestone, Ian C. 2000 Primary glass sources in the mid first millennium AD. *Annales du 14e Congrès de l'Association Internationale pour l'Histoire du Verre.* Amsterdam: Association Internationale pour l'Histoire du Verre. pp. 111 – 115.

Freestone, Ian C., Leslie, K. A., Thirlwall, M. and Gorin-Rosin, Y. 2003a Strontium isotopes in the investigation of early glass production: Byzantine and Early Islamic glass from the Near East. *Archaeometry* 45 (1): 19 – 32.

Freestone, Ian C., Stapleton, Colleen P. and Rigby, Valery 2003b The production of red glass and enamel in the Late Iron Age, Roman and Byzantine periods. From Chris Entwistle (Ed.) *Through a Glass Brightly: studies in Byzantine and Medieval art and archaeology presented to David Buckton.* Oxford: Oxbow. pp. 142 – 154.

Friedman, Florence Dunn (ed.) 1998 *Gifts of the Nile: ancient Egyptian faience.* London: Thames and Hudson.

Gage, John 1993 *Colour and Culture: practice and meaning from Antiquity to abstraction.* London: Thames and Hudson.

Garner, H. 1956 An early piece of glass from Eridu. *Iraq* 18: 147 – 149.

Garrison, Barbara J. 2001 Molecular dynamics simulations: the theoretical partner to Static SIMS experiments. In John C. Vickerman and David Briggs *Tof-SIMS: surface*

analysis by mass spectrometry. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 223 – 257.

Geilman, V. V. 1955 Die chemische Zusammensetzung einiger alter Gläser. *Glastechnische Berichte* 28. 146—156.

Gell, Alfred 1998 *Art and Agency: an anthropological theory*. Oxford: Clarendon.

Giddy, Lisa L. 1987 *Egyptian Oases: Bahariya, Dakhla, Farafra and Kharga during Pharaonic times*. Warminster: Aris and Phillips Ltd.

Gillis, Carole 2004 The use of colour in the Aegean Bronze Age. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World*. BAR International Series 1267. Oxford: Archaeopress. pp. 56 - 60.

Gilmore, Ian 2001 Optimisation of operating conditions. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 261 – 283.

Goldstein, Sidney M. 1979 *Pre-Roman and Early Roman Glass*. New York: the Corning Museum of Glass.

Goodhew, Peter J., Humphreys, John and Beanland, Richard 2001 *Electron Microscopy and Analysis*. Third Edition. London: Taylor and Francis.

Gosden, Chris 2001 Making sense: archaeology and aesthetics. *World Archaeology* 33 (2): 163 – 167.

Gosden, Chris 2005 Comments III: is science a foreign country? Comments on A. Jones, 'Archaeometry and materiality: materials-based analysis in theory and practice', *Archaeometry* 46 (3), 327 – 338, 2004, and reply. *Archaeometry* 47 (1): 175 – 207.

Green, Lorna R. and Hart, F. Alan 1987 Colour and chemical composition in ancient glass: an examination of some Roman and Wealden glass by means of Ultraviolet-Visible-Infra-red Spectrometry and Electron Microprobe Analysis. *Journal of Archaeological Science* 14: 271- 282.

Grose, David Frederick 1989 *Early Ancient Glass: core-formed, rod formed and cast vessels and objects from the Late Bronze Age to the Early Roman Empire, 1600 BC to AD 50*. New York: Hudson Hills Press.

Gunter, Ann C. 2000 Material, technology and techniques in artistic production. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 1539 - 1551.

Hallo, W. 1992 Trade and traders in the ancient Near East: some new perspectives. In D. Chaplin and F. Joannes (eds.) *La Circulation des Biens, des Personnes et des Idées dans le Proche-Orient Ancien*. Actes de XXXVIII[e] Rencontre Assyriologique Internationale (Paris, 8 – 10 juillet 1991). Paris: Editions Recherche sur les Civilisations, pp. 351 – 356.

Hamell, G. R. 1983 Trading in metaphors: the magic of metaphors. In C. F. Hayes (ed.) *Proceedings of the 1982 Glass Trade Bead Conference*. Rochester, NY: Rochester Museum and Sciences Centre. pp. 5 – 28.

Harden, Donald B. 1968 Ancient Glass, I: pre-Roman. *Archaeological Journal* 125: 46 – 72.

Harden, Donald B. 1979 *The Constable-Maxwell Collection of Ancient Glass: the property of Mr and Mrs Andrew Constable-Maxwell including a Late Roman diatretum or cage cup circa 300 A.D.* London: Sotheby Parke Bernet and Co.

Hatton, G. D., Shortland, A. J. and Tite M. S. 2008 The production technology of Egyptian blue and green frits from second millennium BC Egypt and Mesopotamia. *Journal of Archaeological Science* 35: 1591 – 1604.

Hayes, John W. 1975 *Roman and Pre-Roman Glass in the Royal Ontario Museum.* Toronto: Royal Ontario Museum.

Heck, M. and Hoffmann, P. 2000 Coloured opaque glass beads of the Merovingians. *Archaeometry* 42: 341 – 357.

Heck, M., Rehren, Th. and Hoffmann, P. 2003 The production of lead-tin yellow at Merovingian Schlietheim (Switzerland). *Archaeometry* 45 (1): 33 – 44.

Hegmon, Michelle 1992 Archaeological research on style. *Annual Review of Anthropology* 21: 517 – 536.

Henderson, Julian 1985 The raw materials of early glass production. *Oxford Journal of Archaeology* 4: 267 – 291.

Henderson, Julian 1988a Electron probe microanalysis of mixed-alkali glasses. *Archaeometry* 30 (1): 77 – 91.

Henderson, Julian 1988b Glass production and Bronze Age Europe. *Antiquity* 62: 435 – 451.

Henderson, Julian 1997 Scientific analysis of glass and glaze from Tell Brak and its archaeological significance. In D. Oates, J. Oates and H. McDonald 1997 *The Excavations at Tell Brak 1: The Mitanni and Old Babylonian Periods.* Cambridge: McDonald Institute Monographs. pp. 94 – 100.

Henderson, Julian 2000 *The Science and Archaeology of Materials.* London: Routledge.

Henderson, Julian 2001 Glass and glazes. In D. R. Brothwell and A. M. Pollard (eds.) *Handbook of Archaeological Sciences.* John Wiley and Sons, Ltd. pp. 471 – 482.

Henderson, Julian, McLoughlin, S. D. and McPhail, D. S. 2004 Radical changes in Islamic glass technology: evidence for conservatism and experimentation with new glass recipes from Early and Middle Islamic Raqqa, Syria. *Archaeometry* 46 (3): 439 – 468.

Henderson, Julian, Evans, J. A., Sloane, H. J., Leng, M. J. and Doherty, C. 2005 The use of oxygen, strontium and lead isotopes to provenance ancient glasses in the Middle East. *Journal of Archaeological Science* 32: 665 – 673.

Henderson, Julian, Evans, Jane and Nikita, Kalliopi 2010 Isotopic evidence for the primary production, provenance and trade of Late Bronze Age glass in the Mediterranean. *Mediterranean Archaeology and Archaeometry, MMA* 10: 1 – 24.

Hill, Rowland 2001 Primary ion beam systems. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry.* Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 95 – 111.

Hoffmann, Erwin and Lüdke, Christian 2005 The ICP-ToF mass spectrometer: an alternative for elemental analysis. *Spectroscopy Europe* 17 (1): 16 – 21.

Hosler, Dorothy 1994 *The Sounds and Colours of Power.* Cambridge, Mass.: MIT Press.

Hosler, Dorothy 1995 Sound, colour and meaning in the metallurgy of ancient West Mexico. *World Archaeology* 27 (1): 100 – 115.

Hughes-Brock, Helen 1998 Greek beads of the Mycenaean period (ca.1650 – 1100 BC): the age of the heroines of Greek tradition and mythology. In Sciama, Lidia D. and Eicher, Joanne B. (eds.) *Beads and Bead Makers: gender, material culture and meaning*. Oxford: Berg. pp. 247 – 271.

Hughes-Brock, Helen 2003 The Mycenaean Greeks – master bead makers; major work since Beck. In Ian C. Glover, Helen Hughes-Brock and Julian Henderson (eds.) *Ornaments from the Past: bead studies after Beck*. London: The Bead Study Trust. pp. 10 – 22.

Hurcombe, Linda 2007 A sense of materials and sensory perception in concepts of materiality. *World Archaeology* 39 (4): 532 – 545.

Ignatiadou, D. 2002 Colourless glass in Late Classical and Early Hellenistic Macedonia. *Journal of Glass Studies* 44: 11 – 24.

Ingram, Rebecca Suzanne 2005 *Faience and Glass Beads from the Late Bronze Age Shipwreck at Ulu Burun*. Unpublished thesis for Master of Arts degree presented at Texas A&M Museum.

Jackson, Caroline M. 2005 Glass making in Bronze-Age Egypt. *Science* 308: 1750 – 1752.

Jackson, Caroline M. and Nicholson, Paul T. 2007 Compositional analysis of the vitreous materials found at Amarna. In Nicholson, Paul T. *Brilliant Things for Akhenaten: the production of glass, vitreous materials and pottery at Amarna site 045.1*. London: Egypt Exploration Society. pp. 101 - 116.

Jackson, Caroline M. and Nicholson, Paul T. 2010 The provenance of some glass ingots from the Uluburun shipwreck. *Journal of Archaeological Science* 37: 295 – 301.

Jackson, Caroline M., Nicholson, Paul T. and Gneisinger, W. 1998 Glassmaking at Tell El-Amarna: an integrated approach. *Journal of Glass Studies* 40: 11 – 23.

Jackson, Caroline M., Booth, C. A. and Smedley, J. W. 2005 Glass by design? Raw materials, recipes and compositional data. *Archaeometry* 47 (4): 781 – 795.

James, F. W. and McGovern, P. E. 1986 *The Late Bronze Age at Beth Shan: a study of levels VII and VIII*. Philadelphia: University Museum.

Jameson, Kimberly A. 2005 Culture and cognition: what is universal about the representation of colour experience? *Journal of Cognition and Culture* 5 (3 - 4): 1 – 48.

Jones, Andrew 2004 Archaeometry and materiality: materials-based analysis in theory and practice. *Archaeometry* 46: 327 – 338.

Jones, Andrew and Bradley, R. 1999 The significance of colour in European archaeology. *Cambridge Archaeological Journal* 9 (1): 112 – 114.

Jones, Andrew and MacGregor, Gavin 2002 Wonderful things – colour studies in archaeology from Munsell to materiality. In Andrew Jones and Gavin MacGregor (eds.) *Colouring the Past: the significance of colour in archaeological research*. Oxford: Berg. pp. 1 – 22.

Jones, I. P. 1992 *Chemical Microanalysis Using Electron Beams*. London: The Institute of Materials.

Kaczmarczyk, Alexander 1987 The source of cobalt in ancient Egyptian pigments. In J. S. Olin and J. Blackman (eds.) *Proceedings of the 24th International Symposium on Archaeology*. Smithsonian Institution Press. pp. 369 – 376.

Kaczmarczyk, Alexander and Hedges, Robert E. M. 1983 *Ancient Egyptian Faience: an analytical survey of Egyptian faience from Predynastic to Roman times.* Warminster: Aris and Phillips Ltd.

Kaplan, F.S. 1985 The measuring, mapping and meaning of pots. *American Anthropologist* 87 (2): 357 – 364

Keller, C. A. 1983 Problems in dating glass industries of the Egyptian New Kingdom: examples from Malkata and Lisht. *Journal of Glass Studies* 25: 19 – 28.

Kemp, Barry J. 1979 Wall paintings from the workmen's village at el-Amarna. *Journal of Egyptian Archaeology* 65: 52 – 53.

Kemp, Barry J. 1987 The Amarna workmen's village in retrospect. *Journal of Egyptian Archaeology* 73: 46.

Kemp, Barry J. 1989a *Amarna Reports V.* London: Egypt Exploration Society.

Kemp, Barry J. 1989b *Ancient Egypt: anatomy of a civilisation.* London: Routledge.

Killick, D. 2005 Comments IV: is there really a chasm between archaeological theory and archaeological science? Comments on A. Jones, 'Archaeometry and materiality: materials-based analysis in theory and practice', *Archaeometry* 46 (3), 327 – 338, 2004, and reply. *Archaeometry* 47 (1): 175 – 207.

Knapp, A. Bernard 1998 Mediterranean Bronze Age trade: distance, power and place. In Eric H. Cline and Diane Harris-Cline (eds.) *The Aegean and the Orient in the Second Millennium: proceedings of the 50th Anniversary Symposium, Cincinnati, 18 – 20 April 1997.* Liège: Histoire de l'Art et Archéologie de la Grèce Antique. pp. 193 – 207.

Kücükerman, Önder 1995 Anatolian glass beads: the final traces of three millennia of glassmaking in the Mediterranean region. In Marianne Rasmussen, Ulla Lund Hansen and Ulf Näsman (Eds.) *Glass Beads: cultural history, technology, experiment and archaeology.* Studies in Technology and Culture Vol. 2. Lejre: Historial-Archaeological Experimental Centre. pp. 97 - 102.

Lahlil, S., Biron, I., Galoisy, L. and Morin, G. 2008 Rediscovering ancient glass technologies through the examination of opacifier crystals. *Applied Physics A: materials science and processing* 92: 109 – 116.

Lahlil, S., Biron, I., Cotte, M., Susini, J. and Menguy, N. 2010 Synthesis of calcium antimonite nano-crystals by the 18th dynasty Egyptian glassmakers. *Applied Physics A: materials science and processing* 98: 1 – 8.

Lambert, Joseph B. 1997 *Traces of the Past: unravelling the secrets of archaeology through chemistry.* Massachusetts: helix Books / Addison-Wesley.

B. Landau and Gleitman, L.R. 1985 Language and Experience: evidence from the blind child, Cambridge, MA: Harvard University Press.

Landsberger, B. 1967 *Materialen Zum Sumerischen Lexicon* 9. Rome: Pontifical Biblical Institute.

Lechtman, Heather 1984 Andean value systems and the development of prehistoric metallurgy. *Technology and Culture* 25 (1): 1 – 36.

Lee, J.L.S. and Gilmore, I.S. 2009 The application of multivariate data analysis techniques in surface analysis. In John C. Vickerman and Ian S. Gilmore (Eds.) *Surface*

Analysis – the principal techniques. 2nd Edition. Sussex: John Wiley and Sons Ltd. pp. 563 - 605.

Lemche, Niels Peter 2000 The history of ancient Syria and Palestine: an overview. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 1195 - 1399.

Leprohon, Ronald J. 2000 Royal ideology and state administration in Pharaonic Egypt. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 273 - 329.

Lesko, Leonard H. (ed.) 1994 *Pharaoh's Workers: the villagers of Deir el Medina*. Ithaca and London: Cornell University Press.

Leslie, K. A., Freestone, I. C., Lowry, D. and Thirlwall, M. 2006 The provenance and technology of Near Eastern glass: oxygen isotopes by Laser Fluorination as a compliment to strontium. *Archaeometry* 48 (2): 253 – 270.

Lierke, Rosemarie, Birkhall, Frederick and Molnar, Pavel 1995 Experimental reproduction of spiral beads. In Marianne Rasmussen, Ulla Lund Hansen and Ulf Näsman (Eds.) *Glass Beads: cultural history, technology, experiment and archaeology*. Studies in Technology and Culture Vol. 2. Lejre: Historial-Archaeological Experimental Centre. pp. 117 - 119.

Lilyquist, Christine 1995 *Egyptian Stone Vessels: Khian through Tuthmosis IV*. New York: The Metropolitan Museum of Art.

Lilyquist, Christine 2005 Egypt and the Near East: evidence of contact in the material record. In C. H. Roehrig , R. Dreyfuss and C. A. Keller (eds.) *Hatshepsut from Queen to Pharoah*. New York: Metropolitan Museum of Art. pp. 60 – 67.

Lilyquist, Christine and Brill, R. H. 1993 *Studies in Early Egyptian Glass*. New York: The Metropolitan Museum of Art.

Liverani, Mario 2000 The Great Powers' Club. In Raymond Cohen and Raymond Westbrook (eds.) *Amarna Diplomacy: the beginnings of international relations*. Baltimore and London: The John Hopkins University Press. pp. 15 – 27.

Lloyd, Seton 1961 *The Art of the Ancient Near East*. London: Thames and Hudson.

Lucas, A. and Harris, J. R. 1962 *Ancient Egyptian Materials and Industries*. 4th Edition. London.

Macqueen, J. G. 1986 *The Hittites and their Contemporaries in Asia Minor*. 2nd Edition. London: Thames and Hudson.

Macqueen, J. G. 2000 The history of Anatolia and of the Hittite Empire: an overview. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 1085 – 1105.

Maidman, Maynard Paul 2000 Nuzi: portrait of an Ancient Mesopotamian provincial town. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 931 - 947.

Markoe, Glenn E. 2000 *Phoenicians*. London: British Museum Press.

Martinón-Torres, Marcos 2008 Why should archaeologists take history and science seriously? In Marcos Martinón-Torres and Thilo Rehren (eds.) *Archaeology, History and Science: integrating approaches to ancient materials*. CA: Left Coast Press. pp. 15 – 36.

Martinón-Torres, Marcos and Rehren, Thilo (eds.) 2008 *Archaeology, History and Science: integrating approaches to ancient materials*. CA: Left Coast Press.

Mass, Jennifer L., Stone, Richard E. and Wypiski, Mark T. 1998 The mineralogical and metallurgical origins of Roman opaque coloured glasses. In Patrick McCray (ed.) *The Prehistory and History of Glassmaking Technology*. Ceramics and Civilisation volume VIII. Westerville, Ohio: The American Ceramic Society. pp. 121 – 144.

Mass, Jennifer L., Wypiski, Mark T. and Stone, Richard E. 2002 Malkata and Lisht glassmaking technologies: towards a specific link between second millennium BC metallurgists and glassmakers. *Archaeometry* 44 (1): 67 – 82.

Mass, Jennifer L. and Stone, Richard E. 2003 Comments on J. L. Mass, M. T. Wypiski and R. E. Stone, 'Malkata and Lisht glassmaking technologies: towards a specific link between second millennium BC metallurgists and glassmakers' *Archaeometry*, 44 (1) (2002), 67 – 82, and reply. Reply. *Archaeometry* 45 (1): 191 – 198.

Matheson, Susan B. 1980 *Ancient Glass in the Yale University Art Gallery*. Yale University Art Gallery.

Matthews, Donald 2000 Artists and artisans in Western Asia. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 455 - 467.

Matthews, R. 2003 *The Archaeology of Mesopotamia*. London: Routledge.

McCray, P. and Kingery, D. 1998 *The Prehistory and History of Glassmaking Technology*. Ceramics and Civilisation 8. Ohio: American Ceramics Society.

McDonald, Helen 1997 The beads. In D. Oates, J. Oates and H. McDonald 1997 *The Excavations at Tell Brak 1: The Mitanni and Old Babylonian Periods*. Cambridge: McDonald Institute Monographs. pp. 101 - 103.

McGovern, Patrick E. 1986a *The Late Bronze and Early Iron Ages of Central Trans Jordan: the Baq'ah Valley Project, 1977 – 1981*. Philadelphia: University Museum.

McGovern, Patrick E. 1986b The chemical discrimination by PIXE analysis of imported and domestic silicate artefacts from Beth Shan. In *Analytical Tools in Archaeometry*. Newark Del.: Bartol Research Foundation of the Franklin Institute.

McGovern, Patrick E. 1992 Silicate industries of Late Bronze – Early Iron Palestine: technological interaction between Egypt and the Levant. In M. Bimson and I. C. Freestone (eds.) *Early Vitreous Materials*. British Museum Occasional Paper 56. London: British Museum. pp. 91 – 114.

McGovern, Patrick E., Fleming, Stuart J. and Swann, Charles P. 1991 The beads from tomb B10a b27 at Dinkha Teppe and the beginnings of glassmaking in the ancient Near East. *American Journal of Archaeology* 95 (3): 395 – 402.

McGovern, Patrick E., Fleming, Stuart J. and Swann, Charles P. 1993 The Late Bronze Age Egyptian garrison at Beth Shan: glass and faience production and importation in the Late New Kingdom. *Bulletin of the American Schools of Oriental Research*, No. 290/291 (May - Aug., 1993): pp. 1-27.

Meeks, N. 1988 Backscattered electron imaging of archaeological material. In S. L. Olsen (ed.) *Scanning Electron Microscopy in Archaeology* BAR International Series 452. Oxford: Archaeopress. pp. 23 – 44.

Merkel, J. F. 1990 Experimental reconstruction of Bronze Age copper smelting based on archaeological evidence from Timna. In B. Rothenberg (Ed.) *The Ancient Metallurgy of Copper*. London: IAMS.

Michalowski, Kazimierz 1977 *The Art of Ancient Egypt*. New York: Abrams.

Miller, D. 2002 Smelter and smith: Iron Age metal fabrication technology in southern Africa. *Journal of Archaeological Science* 29 (10): 1083 – 1131.

Miller, Heather Margaret-Louise 2007 *Archaeological Approaches to Technology*. London: Elsevier.

Moorey, P. R. S. 1994 *Ancient Mesopotamian Materials and industries: the archaeological evidence*. Oxford: Clarendon Press.

Moorey, P. R. S. 2001 The mobility of artisans and opportunities for technology transfer between Western Asia and Egypt in the Late Bronze Age. In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 1 – 14.

Moran, William L. 1987 *The Amarna Letters*. London: The John Hopkins University Press.

Moreland, J. 2001 *Archaeology and Text*. London: Duckworth.

Murnane, William J. 2000 The history of Ancient Egypt: an overview. In Jack M. Sasson, John Baines, Gary Beckman and Karen S. Rubinson (Eds.) *Civilizations of the Ancient Near East*. Massachusetts: Hendrickson. pp. 691 - 711.

Muskett, Georgina 2007 *Mycenaean Art: a psychological approach*. BAR International Series 1636. Oxford: Archaeopress.

Needham, S. 2005 Comments VI: rationalising materiality. Comments on A. Jones, 'Archaeometry and materiality: materials-based analysis in theory and practice', *Archaeometry* 46 (3), 327 – 338, 2004, and reply. *Archaeometry* 47 (1): 175 – 207.

Nenna, M. D. (ed.) 2000 *La route du verre: ateliers primaires et secondaires de verriers du second millionaire av. J.-C. au Moyen-Age*. Travaux de la Maison de l'Orient Méditerranéen no. 33.

Newberry, Percy E. 1920 A glass chalice of Tuthmosis III. *The Journal of Egyptian Archaeology* 6 (3): 155 – 160.

Newton, R. G. 1978 Colouring agents used by medieval glassmakers. *Glass Technology* 19: 59 – 60.

Newton, R. G. and Davison, S. 1996 *Conservation of Glass* Oxford: Butterworth-Heinemann Ltd.

Nicholson, Paul T. 1993 *Egyptian Faience and Glass*. Shire Egyptology Series. Buckinghamshire: Shire Press.

Nicholson, Paul T. 1995a Glassmaking and glassworking at Amarna: some new work. *Journal of Glass Studies* 37: 11 – 19.

Nicholson, Paul T. 1995b Recent excavations at an ancient Egyptian glassworks: Tell el-Amarna 1993. *Glass Technology* 36: 125 – 128.

Nicholson, Paul T. 1997 Early glass and glazing in Egypt: new excavations at Tell el-Amarna. In Anthony Sinclair, Elizabeth Slater and John Gowlett (eds.) *Archaeological*

Sciences: proceedings of a conference on the application of scientific techniques to the study of archaeology. Liverpool, July 1995. Oxford: Oxbow Books. pp. 49 – 53.

Nicholson, Paul T. 1998 Materials and technology. In Florence Dunn Friedman (ed.) *Gifts of the Nile: ancient Egyptian faience*. London: Thames and Hudson. pp. 50 – 64.

Nicholson, Paul T. 1999 Tell el-Amarna glass project (site 045.1). Fieldwork. *Journal of Egyptian Archaeology* 85: 18 – 20.

Nicholson, Paul T. 2006 Glass vessels from the reign of Thutmose III and a hitherto unknown glass chalice. *JGS* 48: 11 – 21.

Nicholson, Paul T. 2007 *Brilliant Things for Akhenaten: the production of glass, vitreous materials and pottery at Amarna site 045.1*. London: Egypt Exploration Society.

Nicholson, Paul T. and Jackson, C. 1998 Kind of blue: glass of the Amarna period replicated. In P. McCray and D. Kingery *The Prehistory and History of Glassmaking Technology*. Ohio: The American Ceramic Society. pp. 105 – 120.

Nicholson, Paul T. and Jackson, C. M. 2000 Tell El-Amarna and the glassmakers' workshop of the second millennium BC. In M. D. Nenna (ed.) *La Route du Verre: ateliers primaries et secondaires du second millenaire av. J. C. au Moyen Âge*. Travaux de la Maison de L'Orient Méditerranéen No. 33. Lyon: Maison de L'Orient Méditerranéen.

Nicholson, Paul T. and Shaw, Ian 2000 *Ancient Egyptian Materials and Technology*. Cambridge: Cambridge University Press.

Nicholson, Paul T., Jackson, Caroline M. and Trott, Katharine M. 1997 The Ulu Burun glass ingots, cylindrical vessels and Egyptian glass. *Journal of Egyptian Archaeology* 83: 143 – 153.

Nightingale, Georg 1998 Glass and the Mycenaean palaces of the Aegean. In Patrick McCray (ed.) *Ceramics and Civilisation volume VIII. The Prehistory and history of Glassmaking Technology*. Ohio: The American Ceramic Society. pp. 205 – 226.

Nikita, Kalliopi 2003 Mycenaean glass beads: technology, forms and function. In Ian C. Glover, Helen Hughes-Brock and Julian Henderson (eds.) *Ornaments from the Past: bead studies after Beck*. London: The Bead Study Trust. pp. 23 – 37.

Nikita, Kalliopi and Henderson, Julian 2006 Glass analyses from Mycenaean Thebes and Elateia: compositional evidence for a Mycenaean glass industry. *Journal of Glass Studies* 48: 71 - 120.

Nolte, Brigit 1968 *Die Glasgefäße im Alten Ägypten*. Berlin: Bruno Hessling.

Nolte, Brigit 1969 An Egyptian glass vessel in the Metropolitan Museum of Art. Notes. *The Metropolitan Museum of Art Journal*: 167 – 171.

Oates, D., Oates, J. and McDonald, H. 1997 *The Excavations at Tell Brak 1: The Mitanni and Old Babylonian Periods*. Cambridge: McDonald Institute Monographs.

Olmo Lete, G. and Molterno Fenellós, J.L. 1999 *Archaeology of the Upper Syrian Euphrates: the Tishrin Dam area*. Proceedings of the International Symposium Held at Barcelona, January 28th – 30th 1998. Barcelona: Editorial Ausa.

Olsen, S. L. (ed.) 1988 *Scanning Electron Microscopy in Archaeology* BAR International Series 452. Oxford: Archaeopress.

Oppenheim, A. Leo 1970 The Cuneiform texts. In A. Leo Oppenheim, Robert H. Brill, Axel Von Saldern and Dan Barag *Glass and Glassmaking in Ancient Mesopotamia: an*

edition of the cuneiform texts which contain instructions for glassmakers with a catalogue of surviving objects. The Corning Museum of Glass Monographs Volume III. Corning: The Corning Museum of Glass Press. pp. 2 – 101.

Oppenheim, A. Leo 1973a A note on research in Mesopotamian glass. *Journal of Glass Studies* 15: 9 – 11.

Oppenheim, A. Leo 1973b Towards a history of glass in the ancient Near East. *Journal of the American Oriental Society* 93 (3): 259 – 266.

Oppenheim, A. Leo, Brill, Robert H., Barag, Dan and Von Saldern, Axel 1970 *Glass and Glassmaking in Ancient Mesopotamia: an edition of the cuneiform texts which contain instructions for glassmakers with a catalogue of surviving objects*. The Corning Museum of Glass Monographs Volume III. Corning: The Corning Museum of Glass Press.

Pagès-Camagna, S. and Colinart, S. 2003 The Egyptian green pigment: its manufacturing process and links to Egyptian blue. *Archaeometry* 45 (4): 637 – 658.

Panagiotaki, M. 1999 Minoan faience- and glass-making: techniques and origins. In P. Betancourt, V. Kavageorghis, R. Laffineur and W. Niemeier (Eds.) ΜΕΛΕΤΗΜΑΤΑ, *Aegeum* 20. pp. 617 – 623.

Paynter, Sarah and Tite, Michael 2001 The evolution of glazing technologies in the ancient Near East and Egypt. In In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 239 – 254.

Peltenberg, E. 1971 Some early developments of vitreous materials. *World Archaeology* 3: 6 – 12.

Pendlebury, John D. S. 1951 *The City of Akhenaten Part III: the central city and the official quarters*. The Excavations at Tell El-Amarna during the seasons 1926 – 1927 and 1931 – 1936. Volume One: text. London: Egypt Exploration Society.

Peters, Mark 2008 Colour use and symbolism in Bronze Age Crete: exploring social and technological relationships. In Caroline M. Jackson and Emma C. Wager (eds.) *Vitreous Materials in the Late Bronze Age Aegean*. Oxford: Oxbow. pp. 187 – 208.

Petrie, W. M. F. 1894 *Tell el-Amarna*. London: Methuen.

Politis, Konstantinos D. (in press) *Excavations at Deir 'Ain 'Abata*. London: British Museum Press.

Pollard, A. M. and Heron, C. 1996 *Archaeological Chemistry*. Cambridge: The Royal Society of Chemistry.

Pollard, A. M., Batt, C. M., Stern, B. and Young, S. M. M. 2007 *Analytical Chemistry in Archaeology*. Cambridge: Cambridge University Press.

Pulak, Cemal 1998 The Uluburun shipwreck: an overview. *The International Journal of Nautical Archaeology and Underwater Exploration* 27 (3): 188 – 224.

Pulak, Cemal and Frey, Donald A. 1985 The Search for a Bronze Age Shipwreck. *Archaeology* 38 (4): 18 – 24.

Quirke, Stephen 2001 Colour vocabularies in Ancient Egypt. In W. V. Davies (ed.) *Colour and Painting in Ancient Egypt*. London: The British Museum Press. pp. 186 – 192.

Ragai, Jehane 1986 Colour: its significance and production in Ancient Egypt. *Endeavour* 10(2): 74 – 79.

Reed, S. J. B. 1993 *Electron Microprobe Analysis* 2nd Edition. Cambridge: Cambridge University Press.

Rehren, Thilo 1997 Ramesside glass-colouring crucibles. *Archaeometry* 39 (2): 355 – 368.

Rehren, Thilo 2000a New aspects of ancient Egyptian glassmaking. *Journal of Glass Studies* 42: 13 – 24.

Rehren, Thilo 2000b Rationales in Old World base glass compositions. *Journal of Archaeological Science* 27: 1225 – 1234.

Rehren, Thilo 2001 Aspects of the production of cobalt-blue glass in Egypt. *Archaeometry* 43 (4): 483 – 489.

Rehren, Thilo 2003 Comments on J. L. Mass, M. T. Wypiski and R. E. Stone, 'Malkata and Lisht glassmaking technologies: towards a specific link between second millennium BC metallurgists and glassmakers *Archaeometry*, 44 (1) (2002), 67 – 82, and reply' Comments I. *Archaeometry* 45 (1): 185 – 190.

Rehren, Thilo 2008 A review of factors affecting the composition of early Egyptian glasses and faience: alkali and alkali earth oxides. *Journal of Archaeological Science* 35: 1345 – 1354.

Rehren, Thilo and Pusch, Edgar B. 1997 New Kingdom glass-melting crucibles from Qantir-Piramesses. *Journal of Egyptian Archaeology* 83: 127 – 141.

Rehren, Thilo and Pusch, Edgar 1999 Glass and glassmaking at Qantir-Piramesses and beyond. *Egypt and the Levant* 9: 171 – 179.

Rehren, Thilo and Pusch, Edgar 2005 Late Bronze Age glass production at Qantir-Piramesses, Egypt. *Science* 308: 1756 – 1758.

Rehren, Thilo, Pusch, Edgar B. and Herold, Anja 1998 Glass colouring works within a copper-centred industrial complex in Late Bronze Age Egypt. In Patrick McCray (ed.) *Ceramics and Civilisation volume VIII. The Prehistory and History of Glassmaking Technology*. Ohio: The American Ceramic Society. pp. 227 – 250.

Rehren, Thilo, Pusch, Edgar B. and Herold, Anja 2001 Problems and possibilities in workshop reconstruction: Qantir and the organisation of LBA glass working sites. In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 223 - 238.

Reich, D. Fraser 2001 Sample handling. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 113 – 135.

Riederer, J. 1974 Recently identified Egyptian pigments. *Archaeometry* 16 (1): 102 – 109.

Riefstahl, Elizabeth 1968 *Ancient Egyptian Glass and Glazes in the Brooklyn Museum*. New York: The Brooklyn Museum.

Riefstahl, Elizabeth 1972 A unique fish-shaped glass vial in the Brooklyn museum. *Journal of Glass Studies* 14: 11 – 14.

Robins, Gay 1997 *The Art of Ancient Egypt*. London: British Museum Press.

Robson, Eleanor 2001 Society and technology in the Late Bronze Age: a guided tour of the cuneiform sources. In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 39 – 58.

Romano, James F. 2000 Jewellery and personal arts in Ancient Egypt. In Jack M. Sasson (ed.) *Civilisations of the Ancient Near East*. Volume II. Massachusetts: Hendrickson. pp. 1605 – 1621.

Rosch, E. 1972 'Focal' colour areas and the development of names. *Development Psychology* 4: 447 – 455.

Russ, John C. and Russ, J. Christian 2008 *Introduction to Image Processing and Analysis*. Boca Raton, FL: CRC Press.

Rutten, Frank J. M., Henderson, Julian and Briggs, David 2005 Unlocking the secrets of ancient glass technology using ToF-SIMS. *Spectroscopy Europe* 17 (1): 24 – 30.

Rutten, Frank J. M., Roe, Martin J., Henderson, Julian and Briggs, David 2006 Surface analysis of ancient glass artefacts with ToF-SIMS: a novel tool for provenancing? *Applied Surface Science* 252 (19): 7124 – 7127.

Rutten, Frank J. M., Briggs, David, Henderson, Julian and Roe, Martin J. 2009 The application of Time-of-Flight Secondary Ion Mass Spectrometry (ToF-SIMS) to the characterisation of opaque ancient glasses. *Archaeometry* 51 (6): 966 – 986.

Sahlins, M. D. 1976 Colours and cultures. *Semiotica* 16 (1): 1 – 22.

Santopadre, P. and Verita, M. 2000 Analyses of the production technologies of Italian vitreous materials of the Bronze Age. *Journal of Glass Studies* 42: 25 – 40.

Sasson, J. (ed.) 1995 *Civilisations of the Ancient Near East* (4 volumes). New York: Scribner's.

Saunders, Nicholas J. 1999 Biographies of brilliance: pearls, transformations of matter and being *c.* AD 1492. *World Archaeology* 31 (2): 243 – 257.

Saunders, Nicholas J. 2002 The colours of light: materiality and chromatic cultures of the Americas. In Andrew Jones and Gavin MacGregor (eds.) *Colouring the Past: the significance of colour in archaeological research*. Oxford: Berg. pp. 209 – 226.

Sayre, Edward V. 1963 The intentional use of antimony and manganese in ancient glasses. In F. R. Matson and G. E. Rindone (eds.) *Advances in Glass Technology* 2: 263 – 282. New York: Plenum Press.

Sayre, Edward V. and Smith, Ray W. 1961 Compositional categories of ancient glass. *Science* 133: 1824 – 1826.

Sayre, Edward V. and Smith, Ray W. 1967 Some materials of glass manufacturing in antiquity. In M. Levey (ed.) *3rd Symposium on Archaeological Chemistry*. Philadelphia. pp. 279 – 311.

Sayre, Edward V. and Smith, Ray W. 1974 Analytical studies in ancient Egyptian glass. In Bishay, A. (ed.) *Recent Advances in the Science and Technology of Materials*. Vol. 3. New York.

Schenkel, W. 1963 Die Farben in ägyptischer Kunst und Sprache. *Zeitschrift für ägyptische Sprache und Altertumskunde* 88: 137 - 147.

Schiffer, Michael B. 1999 *The Material Life of Human Beings: artefacts, behaviour and communication*. London: Routledge.

Schlick-Nolte, Birgit and Lierke, Rosemary 2002 From silica to glass: on the track of the ancient glass artisans. In Steven Bianchi (Ed.) *Reflections on Ancient Glass from the Borowski Collection*. Bible Lands Museum, Jerusalem. Mainz am Rhein: von Zabern. pp. 11 – 40.

Schlick-Nolte, Birgit and Werthmann, Rainer 2003 Glass vessels from the burial of Nesikhons. *Journal of Glass Studies* 45: 11 – 34.

Schreurs, J. W. and Brill, R. H. 1984 Iron and sulphur related colours in ancient glasses. *Archaeometry* 26 (2): 199 – 209.

Schueler, Bruno W. 2001 Time-of-flight mass analysers. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 75 – 94.

Sciama, Lidia D. 1998 Gender in the making, trading and uses of beads. An introductory essay. In Sciama, Lidia D. and Eicher, Joanne B. (eds.) *Beads and Bead Makers: gender, material culture and meaning*. Oxford: Berg. pp. 1 – 47.

Sciama, Lidia D. and Eicher, Joanne B. (eds.) 1998 *Beads and Bead Makers: gender, material culture and meaning*. Oxford: Berg.

Shelby, J. E. 2005 *Introduction to Glass Science and Technology*. 2nd Edition. Cambridge: The Royal Society of Chemistry.

Sherratt, Andrew 1994 Core, periphery and margin: perspectives on the Bronze Age. In Clay Mathers and Simon Stoddart (eds.) *Development and Decline in the Mediterranean Bronze Age. Sheffield Archaeological Monographs 8*. Somerset: J. R. Collis Publications.

Sherratt, Andrew and Sherratt, Susan 2001 Technological change in the East Mediterranean Bronze Age: capital, resources and marketing. In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 15 – 38.

Sherratt, Susan 2008 Vitreous materials in the Bronze and Early Iron Age. In Caroline M. Jackson and Emma C. Wager (eds.) *Vitreous Materials in the Late Bronze Age Aegean*. Oxford: Oxbow. pp. 209 – 232.

Shortland, Andrew J. 2000a Depictions of glass vessels in two Theban tombs and their role in the dating of early glass. *Journal of Egyptian Archaeology* 86: 159 – 161.

Shortland, Andrew J. 2000b The number, extent and distribution of the vitreous materials workshops at Amarna. *Oxford Journal of Archaeology* 19 (2): 115 – 134.

Shortland, Andrew J. 2000c *Vitreous Materials at Amarna: the production of glass and faience in 18th Dynasty Egypt*. BAR International Series 827. Oxford: Archaeopress.

Shortland, Andrew J. 2001 Social influences on the development and spread of glass. In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 211 – 222.

Shortland, Andrew J. 2002 The use and origin of antimonate colorants in early Egyptian glass. *Archaeometry* 44 (4): 517 – 530.

Shortland, Andrew J. 2003 Comments on J. L. Mass, M. T. Wypiski and R. E. Stone, 'Malkata and Lisht glassmaking technologies: towards a specific link between second

millennium BC metallurgists and glassmakers' *Archaeometry*, 44 (1) (2002), 67 – 82, and reply'. Comments II. *Archaeometry* 45 (1): 190 – 191.

Shortland, Andrew J. 2004 Evaporites of the Wadi Natrun: seasonal and annual variation and its implication for ancient exploration. *Archaeometry* 46 (4): 497 – 516.

Shortland, Andrew J. 2006 Application of lead isotope analysis to a wide range of Late Bronze Egyptian materials. *Archaeometry* 48 (4): 657 – 669.

Shortland, Andrew J. 2007 Who were the glassmakers? Status, theory and method in mid-second millennium glass production. *Oxford Journal of Archaeology* 26 (3): 261 – 274.

Shortland, Andrew J. and Eremin, Katherine 2006 The analysis of second millennium glass from Egypt and Mesopotamia, part 1: new WDS analyses. *Archaeometry* 48 (4): 581 – 603.

Shortland, Andrew J. and Tite, Michael S. 1998 The interdependence of glass and vitreous faience production at Amarna. In Patrick McCray (ed.) *Ceramics and Civilisation volume VIII. The Prehistory and History of Glassmaking Technology*. Ohio: The American Ceramic Society. pp. 251 – 265.

Shortland, Andrew J. and Tite, Michael S. 2000 Raw materials of glass from Amarna and implications for the origins of Egyptian glass. *Archaeometry* 42 (1): 141 – 151.

Shortland, Andrew J., Nicholson, Paul T. and Jackson, Caroline M. 2000 Lead isotopic analysis of eighteenth-dynasty Egyptian eyepaints and lead antimonate colorants. *Archaeometry* 42 (1): 153 – 157.

Shortland, Andrew J., Nicholson, Paul, and Jackson, Caroline 2001 Glass and faience at Amarna: different methods of both supply for production, and subsequent distribution. In Andrew J. Shortland (ed.) *The Social Context of Technological Change: Egypt and the Near East, 1650 – 1550 BC*. Oxford: Oxbow. pp. 147 – 160.

Shortland, Andrew J., Hope, C. A. and Tite, M. S. 2006a Cobalt blue painted pottery from 18th Dynasty Egypt. Geological Society of London Special Publications 2006, v.297: 91 – 99.

Shortland, Andrew J., Schachner, Lukas, Freestone, Ian C. and Tite, Michael S. 2006b Natron as a flux in the early vitreous materials industry: sources, beginnings and reasons for decline. *Journal of Archaeological Science* 33: 521 – 530.

Shortland, Andrew J., Tite, Michael S. and Ewart, I. 2006c Ancient exploitation and use of cobalt alums from the western oases of Egypt. *Archaeology* 48 (1): 153 – 168.

Shortland, Andrew J., Rogers, Nick and Eremin, Katherine 2007 Trace element discriminants between Egyptian and Mesopotamian Late Bronze Age glasses. *Journal of Archaeological Science* 34: 781 – 789.

Shortland, Andrew, Eremin, Katherine and Armstrong, James 2008 Reassessing Bronze Age manufacturing technologies at Nuzi. *Mat. Res. Soc. Symp. Proc.* Volume 1047: 217 – 230.

Shugar, A. N. 2000 Byzantine opaque red glass tesserae from Beit Shean, Israel. *Archaeometry* 42 (2): 375 – 384.

Shugar, A. N. and Rehren, Th. 2002 Formation and composition of glass as a function of firing temperature. *Journal of Glass Technology* 43: 145 – 150.

Sillar, B. and Tite, M. S. 2000 The challenge of 'technological choices' for materials science approaches in archaeology. *Archaeometry* 42 (1): 2 – 20.

Silvestri, A., G. Molin, G. Salviulo and R. Scheivenin 2006 Sand for Roman glass production: an experimental and philological study on source of supply. *Archaeometry* 48 (3): 415 – 432.

Skinner, B. J., Porter, S. C. and Park, J. 2004 *Dynamic Earth: an introduction to physical geology* 5th Edition. USA: John Wiley and Sons, Ltd.

Smirniou, M. and Rehren, Th. 2011 Direct evidence of primary glass production in Late Bronze Age Amarna, Egypt. *Archaeometry* 53 (1): 58 – 80.

Sode, Torben 1995a The traditional use of magic glass beads in the Islamic world. In Marianne Rasmussen, Ulla Lund Hansen and Ulf Näsman (Eds.) *Glass Beads: cultural history, technology, experiment and archaeology*. Studies in Technology and Culture Vol. 2. Lejre: Historial-Archaeological Experimental Centre. pp. 55 – 57.

Sode, Torben 1995b Purdalpur, a glass bead-making village in northern India. In Marianne Rasmussen, Ulla Lund Hansen and Ulf Näsman (Eds.) *Glass Beads: cultural history, technology, experiment and archaeology*. Studies in Technology and Culture Vol. 2. Lejre: Historial-Archaeological Experimental Centre. pp. 103 - 107.

Sode, Torben and Kock, Jan 2001 Traditional raw glass production in northern India: the final stage of an ancient technology. *Journal of Glass Studies* 43: 155 – 169.

Solometo, Julie 2000 *Context and Meaning in Pueblo Mural Painting*. Manuscript of a paper presented at the Chacmool Conference, Anthropology Department, University of Calgary.

Spence, Kate 1999 Red, White and Black: colour in building stone in Ancient Egypt. In 'Viewpoint: what meaning had colour in early societies?' *Cambridge Archaeological Journal* 9(1): 114 – 117.

Starr, R. 1939 *Nuzi*. Volume 1. Cambridge : Harvard University Press.

Stern, E. Marianne 1993 Glass-working before glass blowing. *Annales du 12e Congrès de l'Association Internationale pour l'Histoire du Verre*. Amsterdam: Association Internationale pour l'Histoire du Verre. pp. 21 – 31.

Stern, E. Marianne 1998 Interaction between glassworkers and ceramicists. In Patrick McCray (ed.) *Ceramics and Civilisation volume VIII. The Prehistory and history of Glassmaking Technology*. Ohio: The American Ceramic Society. pp. 183 – 204.

Stern, E. Marianne and Schlick-Nolte, B. 1994 *Early Glass of the Ancient World 1600 BC – AD 50*. Ostfildern: Verlag Gerd Hatje.

Stos-Gale, Z. A. and Gale, N. H. 1981 Sources of galena, lead and silver in Predynastic Egypt. *Review D'Archeometrie*5: 285 – 295.

Strange, John 2001 The Late Bronze Age. In Burton MacDonald, Russell Adams and Potr Bienkowski *The Archaeology of Jordan*. Levantine Archaeology I. Sheffield: Sheffield Academic Press. pp. 291 – 321.

Swann, C. P., McGovern, P. E. and Fleming, S. J. 1990 Colorants used in ancient Egyptian glassmaking: specialised studies using PIXE spectrometry. *Nuclear Instruments and Methods in Physics research*, B45: 311 – 314.

Tait, Hugh 1991 *Five Thousand Years of Glass*. London: British Museum Press.

Tanimoto, Satoko and Rehren, Thilo 2008 Interactions between silicate and salt melts in LBA glassmaking. *Journal of Archaeological Science* 35: 2566 – 2573.

Tatton-Brown, Veronica and Andrews, Carol 1991 Before the invention of glassblowing. In Hugh Tait (ed.) *Five Thousand Years of Glass*. London: British Museum Press. pp. 21 – 61.

Taylor, Timothy 2005 Comments VII: a cunning duplicate in mind – materiality and the interpretive dilemma. Comments on A. Jones, 'Archaeometry and materiality: materials-based analysis in theory and practice', *Archaeometry* 46 (3), 327 – 338, 2004, and reply. *Archaeometry* 47 (1): 175 – 207.

Taylor, Timothy 2008 Materiality. In R. Alexander Bentley, Herbert D. G. Machner and Christopher Chippendale (eds.) *Handbook of Archaeological Theories*. Plymouth: Altamira Press. pp. 297 – 320.

Tilley, C. 1999 *Metaphor and Material Culture*. Oxford: Blackwell.

Tite, Michael S. 1987 Characterisation of early vitreous materials. *Archaeometry* 29 (1).

Tite, Michael S. and Shortland, A. J. 2003 Production technology for copper- and cobalt-blue vitreous materials from the New Kingdom site of Amarna – a reappraisal. *Archaeometry* 45 (2): 285 – 312.

Tite, Michael S., Shortland, Andrew and Paynter, Sarah 2002 The beginnings of vitreous materials in the Near East and Egypt. *Accounts of Chemical Research* 35 (8): 585 – 593

Tite, Michael S., Shortland, A., Maniatis, Y., Kavoussanaki, D. and Harris, S. A. 2006 The composition of the soda-rich and mixed-alkali plant ashes used in the production of glass. *Journal of Archaeological Science* 33: 1284 – 1292.

Tite, Michael S., Pradell, T. and Shortland, A. 2008 Discovery, production and use of tin-based opacifiers in glasses, enamels and glazes from the Late Iron Age onwards: a reassessment. *Archaeometry* 50 (1): 67 – 84.

Tite, Michael S., Maniatis, Y., Kavoussanaki, D., Panagiotaki, M., Shortland, A.J. and Kirk, S.F. 2009 Colour in Minoan faience. *Journal of Archaeological Science* 36: 370 – 378.

Turner, V. 1967 *The Forest of Symbols: aspects of Ndembu ritual*. Ithaca: Cornell University Press.

Turner, W. E. S. 1954 Studies of ancient glass and glass-making processes. Part I. Crucibles and melting temperatures employed in Ancient Egypt at about 1370 BC. *Journal of the society of glass technology* 38: 436 –444.

Turner, W. E. S. 1956a Studies in ancient glasses and glassmaking processes. Part III. The chronology of the glassmaking constituents. *Journal of the Society of Glass Technology* 40: 39 – 52.

Turner, W. E. S. 1956b Studies in ancient glasses and glassmaking processes. Part IV. The chemical composition of ancient glasses. *Journal of the Society of Glass Technology* 40: 162 – 184.

Turner, W. E. S. 1956c Studies in ancient glasses and glassmaking processes. Part V. Raw materials and melting processes. *Journal of the Society of Glass Technology* 40: 277 – 300.

Turner, W. E. S. and Rooksby, N. P. 1959 A study of the opalescing agents in ancient opal glasses throughout three thousand four hundred years. *Glastechnische Ber.* 32K. pp. 17 – 28.

Tyler, Bonnie J. 2001 ToF-SIMS image analysis. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 475 - 493.

Uda, M., Nakamura, M., Yoshimura, S., Kondo, J., Saito, M., Shirai, Y., Hasegawa, S., Baba, Y., Ikeda, K., Ban, Y., Matsuo, A., Tamada, M., Sunaga, H., Oshio, H., Yamashita, D., Nakajima, Y. and Utaka, T. 2002 'Amarna blue' painted on ancient Egyptian pottery. *Nuclear Instruments and Methods in Physics Research B* 189: 382 – 386.

Urbassek, Herbert M. 2001 Status of cascade theory. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 139 - 159.

Van De Mieroop, Marc 2007 *A History of the Ancient Near East ca. 3000 – 323 BC*. 2nd Edition. Malden, USA: Blackwell Publishing.

Van Stipdonk, Michael 2001 Polyatomic primary beams. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 309 - 345.

Vandiver, Pamela 1982 Mid-second millennium BC soda-lime silicate technology at Nuzi (Iraq). In T. A. Wertime and S. F. Wertime (eds.) *Early Pyrotechnology* Smithsonian Institute Press. pp. 73 – 92.

Vandiver, Pamela B. 1983 Glass technology at the mid second millennium BC Hurrian site of Nuzi. *Journal of Glass Studies* 25: 239 – 247.

Vandiver, Pamela B., Swann, Charles and Cranmer, David 1991 A review of mid-second millennium B.C. Egyptian glass technology at Tell El-Amarna. In Pamela B. Vandiver, James Druzik and George Segan Wheeler (eds.) *Materials Issues in Art and Archaeology II*. Symposium held April 17 – 21, 1990, san Fransisco, California, U.S.A. Pittsburgh, Pennsylvania: Materials Research Society.

Vickers, Michael 1998 Antiquity and Utopia: the paradox in glass studies. In Patrick McCray (ed.) *The Prehistory and History of Glassmaking Technology*. Ceramics and Civilisation volume VIII. Westerville, Ohio: The American Ceramic Society. pp. 17 – 31.

Vickerman, John C. 2001 ToF-SIMS – an overview. In John C. Vickerman and David Briggs *Tof-SIMS: surface analysis by mass spectrometry*. Chichester and Manchester: IM Publications and SurfaceSpectra Limited. pp. 1 – 36.

Vogel, Werner 1994 *Glass Chemistry*. Second Edition. Berlin: Springer-Verlag.

Von Saldern, Axel 1968 *Ancient Glass in the Museum of Fine Arts, Boston*. Boston: Museum of Fine Arts, Boston.

Wachsmann, S. 1998 *Seagoing Ships and Seamanship in the Bronze Age Levant*. College Station, TX, London: Texas A. & M. University Press, Chatham.

Waldbaum, Jane C. 1978 *From Bronze to Iron: the transition from the Bronze Age to the Iron Age in the Eastern Mediterranean*. Studies in Mediterranean Archaeology Vol. LIV. Göteborg: Paul Åströms Förlag.

Walton, M. S., Shortland, Andrew, Kirk, S. and Degryse, P. 2009 Evidence for the trade of Mesopotamian and Egyptian glass to Mycenaean Greece. *Journal of Archaeological Science* 36: 1496 – 1503.

Warburton, David A. 2004 The terminology of Ancient Egyptian colours in context. In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World.* BAR International Series 1267. Oxford: Archaeopress. pp. 126 – 130.

Weinstein, James M. 1998 Egyptian relations with the eastern Mediterranean world at the end of the second millennium BCE. In Seymour Gitin, Amihai Mazar and Ephraim Stern (Eds.) *Mediterranean Peoples in Transition: 13th to early 10th centuries BCE.* Jerusalem: Israel Exploration Society.

Westbrook, Raymond 2000 Babylonian diplomacy in the Amarna letters. *Journal of the American Oriental Society* 120 (3): 377 – 382.

Welham, Kate, Jackson, Caroline M. and Smedley, James W. 2003 Colour formation in *sealing wax* red glass. *Annales du 14e Congrès de l'Association Internationale pour l'Histoire du Verre.* Amsterdam: Association Internationale pour l'Histoire du Verre. pp. 11 – 15.

Weyl, W. A. 1976 *Coloured Glasses.* Second Edition. Sheffield: Society of Glass Technology.

Wierzbicka, A. 1990 The meaning of colour terms: semantics, culture, and cognition. *Cognitive Linguistics* 1 (1): 99 – 150.

Woolley, C. L. 1955 Alalakh: an account of the excavations at Tell Atchana in Hatay, 1937 – 49. *Antiquaries' Res. Rept.* No. 18: 299ff.

Woolley, C. L. 1939 *Ur Excavations.* London.

Yoffee, N. 1980 *Explaining Trade in Ancient Western Asia.* Malibu: Undena.

Yon, Marguerite 2000a Ugarit: 6000 years of history (historical data on the Levant and the eastern Mediterranean of the Late Bronze Age). *Near Eastern Archaeology* 63 (4): 186 – 189.

Yon, Marguerite 2000b A Trading City: Ugarit and the West. *Near Eastern Archaeology* 63(4): 192-193.

Zaccagnini, Carlo 1983 Patterns of mobility among ancient Near Eastern craftsmen. *Journal of Near Eastern Studies* 42: 245 – 264.

Zaccagnini, Carlo 2000 The interdependence of the great powers. In Raymond Cohen and Raymond Westbrook (eds.) *Amarna Diplomacy: the beginnings of international relations.* Baltimore and London: The John Hopkins University Press. pp. 141 – 153.

Ziderman, I. Irving 2004 Purple dyeing in the Mediterranean world: characterisation of biblical *Tekhelet.* In Liza Cleland and Karen Stears (eds.) *Colour in the Ancient Mediterranean World.* BAR International Series 1267. Oxford: Archaeopress. pp. 40 – 45.

Appendix 1
Samples and Sample Data

Appendices 2, 3 and 4 should all be read with reference to the information provided below. In particular, please note that the tables provided here give details of codes for the particular object sampled from a group, or which colour of glass is being referred to where a polychrome object was sampled. The column 'List of Microprobe Images' provides a direct correlation with Appendix 4.

1. Samples from Cambridge University Museum of Archaeology and Anthropology

32.385, Amarna XVIII Dynasty

Provenance and Date: String of glass and faience beads. Source is Egypt Exploration Society, 1932, from excavations at Amarna.

Notes: Though labelled as string of beads, this set of items also contains a large number of glass canes in various shades of blue and green and several fused segmented beads.

Notes (analytical): *I* has quite a few small holes which may affect results. *IV* has a very small number of high Z (atomic number) inclusions, and a large number of holes. *V* has some acicular inclusions, similar Z to matrix, too small to analyse, and a fair number of holes. *VIII* appears to be an opaque sample but very few inclusions are visible with the microprobe (less than some samples which appear translucent), possibly reflecting a different cause for opacification, which may be supported by the large number of holes present though these may equally be the remains of inclusions. *IX* has inclusions, which were imaged, but none were larger enough to conduct a separate spot analysis. *X* appears to be a translucent sample but has a very low number of high Z inclusions. *XI* has a number of elongated bubbles, possibly reflecting drawing of cane (these would be invisible in other cane fragments if they were placed 'end on' in the resin). *XIII* showed possible evidence of streaking under microprobe, though inclusions nonetheless fairly evenly dispersed. *XII* has a very large proportion of holes which are likely to negatively affect results of spot analyses. *XIV* is quite weathered and contains some patches of low Z. *XV* has very small specks of inclusions, which were imaged, though none were large enough for a separate spot analysis. *XX* contains a large number of low Z crystallites, though there are also rare high Z inclusions amongst these despite its appearance as a translucent or semi-translucent sample.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.385_	amber	N	32.385mat1 32.385mat2	matrix averaged from 2 point analyses	n/a
32.385I	blue	N	32.385Imat1 32.385Imat2	matrix averaged from 2 point analyses	n/a

(32.385 continued)

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.385II	green	Y	32.385IImat1 32.385IImat2	matrix averaged from 2 point analyses	32,385II (whole sample) / 32.385IIa / 32.385IIb / 32.385IIc / 32.385IId
			32.385IIwhitinc	point analysis of inclusion	32.385e
32.385IV	blue	N	32.385Ivmat1 32.385Ivmat2	matrix averaged from 2 point analyses	32.385IV (whole sample) / 32.385IVa / 32.385IVb / 32.385IVc / 32.385IVd
			32.385IVwhitinc	point analysis of inclusion	32.385IVe
32.385V	green	N	32.385Vmat1 32.385Vmat2	matrix averaged from 2 point analyses	32.385V (whole sample) / 32.385Va / 32.385Vb / 32.385Vc / 32.385Vd
			32.385Vwhitinc	point analysis of inclusion	32.385Ve
32.385VI	blue	N	32.385Vimat1 32.385VImat2	matrix averaged from 2 point analyses	n/a
32.385VII	turquoise	Y	32.385VIImat1 32.385VIImat2	matrix averaged from 2 point analyses	32.385VII (whole sample) / 32.385VIIa / 32.385VIIb / 32.385VIIc / 32.385VIId
			32.385VIIwhitinc	point analysis of inclusion	32.385VIIe
32.385VIII	turquoise	Y	32.385VIIImat1 32.385VIIImat2	matrix averaged from 2 point analyses	32.385VIII (whole sample) / 32.385VIIIa / 32.385VIIIb / 32.385VIIIc / 32.385VIIId
32.385IX	green	N	32.385IXmat1 32.385IXmat2	matrix averaged from 2 point analyses	32.385IX (whole sample) / 32.385IXa / 32.385IXb / 32.385IXc / 32.385IXd
32.385X	green	N	32.385Xmat1 32.385Xmat2	matrix averaged from 2 point analyses	32.385X (whole sample) / 32.385Xa / 32.385Xb / 32.385Xc / 32.385Xd
			32.385Xlgwhitinc	point analysis of relatively large inclusion	32.385Xe
			32.385Xbrinc	point analysis of high Z inclusion	32.385Xf
32.385X2	green	N	32.385X2mat1 32.385X2mat2	matrix averaged from 2 point analyses	32.385X2 (whole sample) / 32.385X2a / 32.385X2b / 32.385X2c / 32.385X2d
			32.385X2lgwhitinc	point analysis of inclusion	32.385X2e
32.385XI	light blue	N	32.385XImat1 32.385XImat2	matrix averaged from 2 point analyses	32.385XI (to show elongated holes)

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.385XII	blue	N	32.385XIImat1 32.385XIImat2	matrix averaged from 2 point analyses	n/a
32.385XIII	green	Y	32.385XIIImat1 32.385XIIImat2	matrix averaged from 2 point analyses	32.385XIII (whole sample) / 32.385XIIIa / 32.385XIIIb / 32.385XIIIc / 32.385XIIId
			32.385XIIIwhitinc1	point analysis of inclusion	32.385XIIIe
			32.385XIIIwhitinc2	point analysis of inclusion	32.385XIIIf
32.385XIV	green	Y	32.385XIVmat1 32.385XIVmat2	matrix averaged from 2 point analyses	32.385XIV (whole sample) / 32.385XIVa / 32.385XIVb / 32.385XIVc / 32.385XIVd
			32.385XIVgwhitinc	point analysis of inclusion	32.385XIVe
			32.385XIVwhitinc	point analysis of inclusion	32.385XIVf
			32.385XIVdkpatch	analysis low Z patch of matrix	see 32.385XIV (whole sample)
32.385XV	dark blue	N	32.385XVmat1 32.385XVmat2	matrix averaged from 2 point analyses	32.385XV (whole sample) / 32.385XVa / 32.385XVb
32.385XVI	turquoise	Y	32.385XVImat1 32.385XVImat2	matrix averaged from 2 point analyses	32.385XVI (whole sample) / 32.385XVIa / 32.385XVIb / 32.385XVIc (area of holes) / 32.385XVId / 32.385XVIe
			32.385XVIinc	point analysis of inclusion	32.385XVIf
32.385XX	blue	N	32.385XXmat1 32.385XXmat2	matrix averaged from 2 point analyses	32.385XX (whole sample) / 32.385XXa / 32.385XXb / 32.385XXc / 32.385XXd
			32.385XXdk	analysis darker patch of matrix	see 32.385XVI (whole sample)
			32.385XXlt	analysis lighter patch of matrix	see 32.385XVI (whole sample)
			32.385XXwhitinc	point analysis of inclusion	32.385XXe

27.1495, Amarna, XVIII Dynasty

Provenance and Date: Listed as string of beads of glass, faience, stone, carnelian. Source is Egypt Exploration Society. Excavated at Amarna.

Notes: A number of small, dark blue beads were present, one of which was sampled.

Notes (analytical): *AII* has a line of weathering around the edge of the sample, visible under microprobe, and a single high Z inclusion.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
27.1495AII	blue	N	27.1495AIImat1 27.1495AIImat2	matrix averaged from 2 point analyses	n/a

32.412, Amarna, XVIII Dynasty

Provenance and Date: Listed as 1932.412 A - H. Amulet. Faience, stone, carnelian, glass. G is glass heart amulet with white, yellow and purple present. Source is Egyptian Exploration Society, excavated at Amarna.

Notes: Glass heart amulet sampled. Base material appears to be a deep purple shade, with bands of white and yellow surrounding it. Appears to be formed around a core or possibly a thicker rod. Some crumbly white material remains in the 'thread hole'.

Notes (analytical): possible separate phase in corner of *32.4123*, analysed as *diffmat1* and *whitinc2*.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.4121yell	yellow	Y	32.4121yellmat1 32.4121yellmat2	matrix averaged from 2 point analyses	32.4121 (whole sample) / 32.4121a (boundaries between colours) / 32.4121b / 32.4121c / 32.4121d / 32.4121e
			32.4121whitinc1	point analysis of inclusion	32.4121n
32.4121wh	white	Y	32.4121whmat1 32.4121whmat2	matrix averaged from 2 point analyses	32.4121 (whole sample) / 32.4121a (boundaries between colours) / 32.4121f / 32.4121g / 32.4121h / 32.4121i
			32.4121whitinc2	point analysis of inclusion	32.4121o
32.4121pur	purple	N	32.412purmat1 32.4121purmat2	matrix averaged from 2 point analyses	32.4121 (whole sample) / 32.4121a (boundaries between colours)
32.4122_	white	Y	32.4122mat1 32.4122mat2	matrix averaged from 2 point analyses	32.412234 (whole sample) / 32.412234a / 32.412234b / 32.412234c / 32.412234d
			32.4122whitinc	point analysis of inclusion	32.412234k

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.4123_	yellow	Y	32.4123matl	matrix averaged from 2 point analyses	32.412234 (whole sample) / 32.412234e / 32.412234f / 32.412234g / 32.412234h
			32.4123mat2		
			32.4123whitincl	point analysis of inclusion	32.412234l
			32.4123diffmatl	analysis of different looking area of matrix	32.412234i / 32.412234j
			32.4123whitinc2	point analysis of inclusion	32.412234m
32.4124_	purple	N	32.4124matl	matrix averaged from 2 point analyses	see 32.412234 (whole sample)
			32.4124mat2		

32.410, Amarna, XVIII Dynasty

Provenance and Date: Listed as 1932.410 A - B. Beads, faience (glass not mentioned in listing). Source is Egypt Exploration Society, excavated at Amarna.

Notes: Includes a black and white glass bead, which was sampled.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.410Awh	white	Y	32.410Awhmatl	matrix averaged from 2 point analyses	32.410A (whole sample) / 32.410Aa / 32.410Ab / 32.410Ac / 32.410Ad
			32.410Awhmat2		
			32.410Awhitinc	point analysis of inclusion	32.410Ae
32.410Ablk	black	N	32.410Ablkmatl	matrix averaged from 2 point analyses	32.410A (whole sample)
			32.410Ablkmat2		

32.408, Amarna, XVIII Dynasty

Provenance and Date: Listed as glass bead. Source is Egypt Exploration Society, excavated at Amarna during the British Museum expedition to Middle Egypt.

Notes: Includes several items of various materials. Some are of glass including one dark blue and yellow piece which was sampled.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.408I	yellow	Y	32.408Imat1 32.408Imat2 32.408Imat3	matrix averaged from 3 point analyses	32.408I (whole sample) / 32.408Ia / 32.408Ib / 32.408Ic / 32.408Id / 32.408Ie / 32.408If
			32.408Iwhitinc1	point analysis of inclusion	32.408Ig
			32.408Iwhitinc2	point analysis of inclusion	32.408Ih
32.408II1	yellow	Y	32.408II1mat1 32.408II1mat2	matrix averaged from 2 point analyses	32.408II12 (whole sample) / 32.408IIa / 32.408IIb / 32.408IIc / 32.408IId
			32.408II1whitinc	point analysis of inclusion	32.408IIe
32.408II2	dark blue	N	32.408II2mat1 32.408II2mat2	matrix averaged from 2 point analyses	see 32.408II12 (whole sample)

32.413, Amarna, XVIII Dynasty

Provenance and Date: Listed as mixed beads on a string. Faience is only material listed in catalogue. Source is Egypt Exploration Society, British Museum Expedition to Middle Egypt, excavated at Amarna.

Notes: This and another string of beads in the same bag include several of glass. Some of the beads have interesting / unusual colour and design features and the ascription of these particular examples (not sampled) to the XVIII Dynasty is questionable, though they may well have been recovered from Amarna or its environs. *III2* is apparently severely weathered and the original colour is therefore impossible to determine.

Notes (analytical): *III2* contains streaks, possibly due to weathering, shown in image *32.413IIIb*.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.413II	dark brown	N	32.413II1mat1 32.413II1mat2	matrix averaged from 2 point analyses	n/a
32.413I2	White	Y	32.413I2mat1 32.413I2mat2	matrix averaged from 2 point analyses	32.413I2 (whole sample) / 32.413I2a / 32.413I2b / 32.413I2c / 32.413I2d
			32.413I2whitinc	point analysis of inclusion	32.413I2e

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.413II	Black	N	32.413IImat1 32.413IImat2	matrix averaged from 2 point analyses	n/a
32.413III1	Blue	N	32.413III1mat1 32.413III1mat2	matrix averaged from 2 point analyses	32.413III (whole sample) / 32.413IIIa
			32.413III1itinc	point analysis of inclusion	32.413IIIa
32.413III2	Blue	N	32.413III2mat1 32.413III2mat2	matrix averaged from 2 point analyses	32.413IIIb

24.908, Amarna, XVIII Dynasty

Provenance and Date: Listed as string of beads. Material listed as faience. Source is Egypt Exploration Society, excavated in 1923 or 1924, at Amarna.

Notes: Although listed as faience in the CUMAA catalogue the item included a number of glass beads, which were sampled.

Notes (analytical): *I* has a large number of holes, which though visible on images were avoided for the EDX analyses.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
24.908Ibl	Black	N	24.908Iblmat1 24.908Iblmat2	matrix averaged from 2 point analyses	see 24.908I (whole sample)
24.908Iwh	White	Y	24.908Iwhmat1 24.908Iwhmat2	matrix averaged from 2 point analyses	24.908I (whole sample) / 24.908Ia / 24.908Ib / 24.908Ic / 24.908Id
			24.908Iwhitinc	point analysis of inclusion	24.908Ie
24.908II	Amber	N	24.908IImat1 24.908IImat2	matrix averaged from 2 point analyses	n/a
24.908III	light green	N	24.908IIImat1 24.908IIImat2	matrix averaged from 2 point analyses	24.908III (whole sample) / 24.908IIIa / 24.908IIIb / 24.908IIIc / 24.908IIId / 24.908IIIe
			24.908IIIwhitinc	point analysis of inclusion	24.908IIIf

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
24.908IV	Yellow	Y	24.908IVmat1 24.908IVmat2	matrix averaged from 2 point analyses	24.908IV (whole sample) / 24.908IVa / 24.908IVb / 24.908IVc / 24.908IVd
			24.908IVwhitinc	point analysis of inclusion	24.908IVe
24.908V	light blue	N	34.908Vmat1	matrix averaged from 2 point analyses	n/a
			34.908Vmat2		

32.407, Amarna, XVIII Dynasty

Provenance and Date: Listed as string of beads: faience; glass. Source is Egypt Exploration Society. Excavated at Amarna.

Notes: Includes 'boat beads', leaf pendants, segmented barrel bead. Some glass here, including two black and white beads similar to others in the collection listed as from Amarna and Ur. Also one yellow opaque and various blue beads present.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.407I	Black	N	32.407Imat1 32.407Imat2	matrix averaged from 2 point analyses	n/a
32.407II	Blue	N	32.407IImat1 32.407IImat2	matrix averaged from 2 point analyses	32.407IIa (whole sample)
32.407III	Yellow	Y	32.407IIImat1 32.407IIImat2	matrix averaged from 2 point analyses	32.407III (whole sample) / 32.407IIIa / 32.407IIIb / 32.407IIIc / 32.407IIId
			32.407IIIwhitinc	point analysis of inclusion	32.407IIIe

32.386, Amarna, XVIII Dynasty

Provenance and Date: Listed as 'bead'. Materials listed as glass, faience. Source is Egypt Exploration Society, excavated at Amarna.

Notes: Assorted fragments of beads. Most are already broken and therefore ideal for sampling. All are in various shades of blue and green.

Notes (analytical): *I* has a large number of holes, particularly concentrated in the area images were taken from. *V* contains a fair number of holes and no very large inclusion: that analysed as *Vwhitinc* may be too small for significant results.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.386I	black	N	32.386Imat1 32.386Imat2	matrix averaged from 2 point analyses	32.386Ia (whole sample) / 32.386Ib / 32.386Ic
32.386II	purple	N	32.386IImat1 32.386IImat2	matrix averaged from 2 point analyses	32.386IIa (whole sample)
32.386IV	turquoise	Y	32.386IVmat1 32.386IVmat2	matrix averaged from 2 point analyses	32.386IVa / 32.386IVb / 32.386IVc
32.386V	dark blue	N	32.386Vmat1 32.386Vmat2	matrix averaged from 2 point analyses	32.386Va (whole sample) / 32.386Vb / 32.386Vc
			32.386Vwhitinc	point analysis of inclusion	32.386Vd
32.386VI	turquoise	Y	32.386VImat1 32.386VImat2	matrix averaged from 2 point analyses	32.386VIa (whole sample) / 32.386VIb / 32.386VIc
			32.386Vwhitinc	point analysis of inclusion	32.386VId

32.395, Amarna, XVIII Dynasty

Provenance and Date: Listed as 'bead'. Materials listed as glass, faience. Source is Egypt Exploration Society, excavated at Amarna.

Notes: Large number of assorted beads, most of which are faience. *III* appears quite heavily weathered.

Notes (analytical): *I* contains a very low number of opacifying inclusions as well as some air bubbles. Its colour suggests it may be the result of mixing (recycling) though this could not be confirmed compositionally.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.395I	light green	N	32.395Imat1 32.395Imat2	matrix averaged from 2 point analyses	32.395Ia
32.395III	amber	N	32.395IIImat1 32.395IIImat2	matrix averaged from 2 point analyses	32.395III (whole sample)

32.404, Amarna, XVIII Dynasty

Provenance and Date: Listed as glass bead. Source is Egypt Exploration Society, excavated at Amarna during the British Museum expedition to Middle Egypt.

Notes: String of glass beads in various shades of blue and green. Some produced by folding over a wire. Most are broken and therefore ideal for minimally destructive sampling.

Notes (analytical): *I* may show evidence of mixing, or the streaks present could be the result of weathering (see images). *II* doesn't contain any inclusions but does have a large number of holes, avoided as much as possible for the EDX analyses, and some possible silica relicts showing as crystals of slightly different Z on the BSE images. *III* has streaks throughout which SE imaging reveals as definite gaps, possibly holes within the glass remaining after a cane or similar was drawn into shape.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.404I	Green	Y	32.404Imat1 32.404Imat2	matrix averaged from 2 point analyses	32.404Ia (whole sample) / 32.303Ib / 32.404Ic
			32.404whitinc1	point analysis of inclusion	32.303Id
32.404II	dark blue	N	32.404IImat1 32.404IImat2	matrix averaged from 2 point analyses	32.404IIa (whole sample) / 32.404IIb / 32.404IIc
32.404III	light blue	N	32.404IIImat1 32.404IIImat2	matrix averaged from 2 point analyses	32.404IIIa (whole sample)

Z1184, Amarna, XVIII Dynasty

Notes: Assortment of faience and glass beads. Most of the larger beads are glass including a turquoise example. A range of colours exists in the smaller glass beads.

Notes (analytical): *I* contains some crystals of a slightly lower Z than the surrounding matrix, possibly relict silica crystals. *IV* contains some bubbles and a number of inclusions, though these were all too small for individual imaging or analysis. *V* was identified as translucent by visual analysis, but it should be noted that this sample contains a number of very small inclusions (imaged).

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
Z1184I	dark blue	N	Z1184Imat1 Z1184Imat2	matrix averaged from 2 point analyses	Z1184Ia (whole sample) / Z1184Ib / Z1184Ic
Z1184II	turquoise	Y	Z1184IImat1 Z1184IImat2	matrix averaged from 2 point analyses	Z1184IIa (whole sample) / Z1184IIb / Z1184IIc
			Z1184IIwhitinc	point analysis of inclusion	Z1184IId

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
Z1184III	turquoise	Y	Z1184IIImat1 Z1184IIImat2	matrix averaged from 2 point analyses	Z1184IIIa (whole sample) / Z1184IIIb / Z1184IIIc
			Z1184IIIwhitinc	point analysis of inclusion	Z1184IIId
Z1184IV	turquoise	Y	Z1184IVmat1 Z1184IVmat2	matrix averaged from 2 point analyses	Z1184IVa (whole sample) / Z1184IVb / Z1184IVc
Z1184V	blue	N	Z1184Vmat1 Z1184Vmat2	matrix averaged from 2 point analyses	Z1184V (whole sample) / Z1184Va / Z1184Vb / Z1184Vc / Z1184Vd

24.1307, Amarna (palace), XVIII Dynasty

Provenance and Date: Listed as assorted fragments of jewellery. Materials listed as faience, glass, ivory. Source is Cyril Fox, excavated at Amarna (palace) by W.M.F. Petrie in 1891 or 1892.

Notes: Chunk of blue raw glass and trail of brown glass, possible sample of frit and vessel wall fragment. The bag also contains pottery, faience, polished stone, gold leaf coated fragment and fragments of glazed tiles, all from the excavation of the palace area at Amarna. (Note that Petrie excavated the palace dumps, so this is may be waste material). *IV* was taken from what appears to be a chunk of 'raw' (unworked) glass.

Notes (analytical): *II*, though translucent, was found to contain a single inclusion which has a significantly higher Z than the surrounding matrix, analysed as *IIwhitinc*.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
24.1307I	Blue	N	24.1307Imat1 24.1307Imat2	matrix averaged from 2 point analyses	see 24.1307Ia (whole sample including IB and IC)
24.1307IB	Turquoise	Y	24.1307IBmat1 24.1307IBmat2	matrix averaged from 2 point analyses	24.1307Ia (whole sample including I and IC) / 24.1307IBa / 24.1307IBb
24.1307IC	Yellow	Y	24.1307ICmat1 24.1307ICmat2	matrix averaged from 2 point analyses	24.1307Ia (whole sample including I and IB) / 24.1307ICa / 24.1307ICb
			24.1307ICwhitinc	point analysis of inclusion	24.1307ICc

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
24.1307II	Amber	N	24.1307IImat1	matrix averaged from 2 point analyses	24.1307IIa (whole sample)
			24.1307IImat2		
			24.1307IIwhitinc	point analysis of inclusion	24.1307IIb
24.1307IV	Turquoise	Y	24.1307IVmat1 24.1307IVmat2	matrix averaged from 2 point analyses	24.1307IVa (whole sample) / 24.1307IVb / 24.1307IVc
			24.1307IVwhitinc	point analysis of inclusion	24.1307IVd

27.1478, Amarna (suburb), XVIII Dynasty

Provenance and Date: Listed as glass scarab. Source is Egypt Exploration Society, British Museum Expedition to Middle Egypt, excavated at Amarna North Suburb.

Notes: Good condition and good for minimally destructive sampling, which was done at the edge of the thread hole. A small turquoise bead was also attached to the same string, but this was deemed too small / fragile for sampling.

Notes (analytical): patches of higher Z quite regularly spaced throughout this sample, though these are possibly associated with weathering. There are also some smaller, comparatively high Z patches which look more like those from deliberately opacified material. The sample contained a large number of holes throughout which may have affected the readings, though SE imaging mode confirmed these do not correspond with the higher Z material which is thought to relate to weathering.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
27.1478_	blue	N	27.1478mat1 27.1478mat2	matrix averaged from 2 point analyses	27.1478 (whole sample) / 27.1478a / 27.1478b / 27.1478c / 27.1478d
			27.1478dkpatch	analysis of area of matrix without inclusions	see 27.1478
			27.1478clustinc	analysis of area with clustered inclusions	27.1478e

47.2472, Abydos, XVIII – XXII Dynasties

Provenance and Date: Listed separately as 1947.2472 A, B, C and D. These are all of the Beck Collection and from Egypt. B and D were listed as coming from Menshiyeh, Abydos. Date range is rather broad: XVIII - XXII Dynasties all cited as possibilities. Gifted by the Egypt Exploration Society. Listings for B (analysed) are: 12 beads, blue and yellow glass oblate beads. From Abydos.

Notes: Opaque yellow and blue. Material was possibly from Menshiyeh, which Newberry (1920) suggested was a location of glass working during the New Kingdom, though Keller (1983, 20) has expressed a number of well founded doubts about this.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2472B	Yellow	Y	1947.2472Bmat1 1947.2472Bmat2	matrix averaged from 2 point analyses	1947.2472B_a (whole sample) / 1947.2472B_b / 1947.2472B_c

47.2473, Abydos, XVIII – XXII Dynasties

Provenance and Date: Listed separately as 1947.2473 A and B. All are from Beck Collection and were excavated at Abydos, dated to between XVIII and XXII Dynasties. A is listed as string of dark red glass oblate beads, stripy black and white and nine blue glass with red line. B is listed as fourteen black and white mottled beads and two small dark red oblate glass beads.

Notes (analytical): *Ai* has an area with a higher number of inclusions, analysed separately. Sample contains a large number of holes, in particular in *Aiii*. Difficult to find an area without holes for point analyses, so they may be negatively affected by this. Note image *Aiiimat2* taken in an area with a large high Z inclusion, so may be considered separately.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2473Ai	White	Y	1947.2473Aimat1 1947.2473Aimat2	matrix averaged from 2 point analyses	1947.2473Ai_a (whole sample) / see also 1947.2473Ai_e (crystal in low inclusion area)
			1947.2473Aiwhitinc1	point analysis of inclusion	1947.2473Ai_d
			1947.2473Aihighinc	analysis of area with higher number of inclusions	1947.2473Ai_b / 1947.2473Ai_c
47.2473Aii	Blue	N	1947.2473Aiimat1 1947.2473Aiimat2	matrix averaged from 2 point analyses	1947.2473Aii_a (whole sample)
47.2473Aiii	red	Y	1947.2473Aiiimat1	matrix	1947.2473Aiii_a (whole sample) / 1947.2473Aiiib / 1947.2473Aiiic /
			1947.2473Aiiimat2	matrix in area of large high Z inclusion	1947.2473Aiii_d

47.2482, Abydos, XX – XXV Dynasties

Provenance and Date: Listed as string of beads of blue copper glass. Source is Beck Collection. Excavated at Abydos (cemetery) by Egypt Exploration Fund. Dated to between XX and XXV Dynasties.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2482i	blue	N	1947.2482imat1 1947.2482imat2	matrix averaged from 2 point analyses	1947.2482i_a (whole sample)
47.2482ii	blue	N	1947.2482iimat1 1947.2482iimat2	matrix averaged from 2 point analyses	1947.2482ii_b (whole sample)

32.471, Matmar, 3rd Intermediate Period

Provenance and Date: Listed as string of beads and amulets of faience, glass and cowrie shells. Source is Louise Clarke. Excavated at Matmar, Egypt, dated to third intermediate period. Found in tomb 1297 by G. Brunton in 1931.

Notes: Bead. Green and opaque white. Length of two joined fragments is 13mm.

Notes (analytical): Sample contains two distinct areas present as streaks under the microscope. These were labelled a and b. Their width made it difficult to be certain a point analysis had not been affected by the close proximity of the other area, however.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.471a	white	Y	1932.471amat1 1932.471amat2	matrix averaged from 2 point analyses	1932.471_a (whole sample) / 1932.471a_b / 1932.471a_c
32.471b	green	N	1932.471bmat1 1932.471bmat2	matrix averaged from 2 point analyses	see 1932.471_a (whole sample)

47.2469, Egypt, XVIII – XIX Dynasties

Provenance and Date: Listed separately as 1947.2469 A - G. All are from Beck Collection, excavated in Egypt and dated to XVIII - XIX Dynasties. Excavator(s) unmentioned. C is listed as seven blue glass ball beads with white spots. E is listed as string of small black, yellow, brown, blue and green glass beads, mostly of oblate shape. G is listed as dating to XVIII Dynasty. Described as string of 23 cylindrical beads of deep yellow glass; three multiple faience beads and a number of small, thin blue disc beads.

Notes: *C* is medium to dark blue, corroded white. Length of bead is 7mm. *E* is opaque dark yellow, green (appears as semi-opaque), and a very dark blue or black area is also present.

Notes (analytical): *Eblu* contains a large number of holes, which may negatively affect results. *Gbl* was identified under visual examination as translucent blue glass, but under the microprobe two distinct areas could be identified, the second and smaller of which is labelled as *Gblii* though it was too small to allow two point analyses of the matrix or inclusion imaging at x500. *Gwh* was identified as a sample of opaque white glass, though this contained an area with no inclusions, analysed as *whnoincarea.*

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2469C	blue	N	1947.2469Cmat1 1947.2469Cmat2	matrix averaged from 2 point analyses	1947.2469C_a (whole sample)
47.2469E blk	black	N	1947.246Eblkmat1 1947.2469Eblkmat2	matrix averaged from 2 point analyses	1947.2469E_a (whole sample E) / 1947.2469Eblk_b (whole sample black)
47.2469E blu	blue	N	1947.2469Eblumat1 1947.2469Eblumat2	matrix averaged from 2 point analyses	1947.2469E_a (whole sample E) / 1947.2469Eblu_c (whole sample blue)
47.2469E yell	yellow	Y	1947.2469Eyell_mat1 1947.2469Eyell_mat2	matrix averaged from 2 point analyses	1947.2469E_a (whole sample E) / 1947.2469Eyell_d (whole sample yellow) / 1947.2469Eyell_i (whole sample low contrast image) / 1947.2469Eyell_f
			1947.2469Eyelllgwhitinc1	point analysis of inclusion	1947.2469yell_g
			1947.2469Eyelllgwhitinc2	point analysis of inclusion	1947.2469Eyell_h
47.2469 Gbli	blue	N	1947.2469Gblimat1 1947.2469Gblimat2	matrix averaged from 2 point analyses	see 1947.2469_Gbl_a (whole sample including Gbli and Gblii)
1947.2469Gbliimatl	?	N	1947.2469Gbliimat1	matrix from 1 point analysis	1947.2469_Gbl_a (whole sample including Gbli and Gblii) / 1947.2469_Gblii_b
47.2469 Gwh	white	Y	1947.2469Gwhmat1 1947.2469Gwhmat2	matrix averaged from 2 point analyses	1947.2469_Gwh_a (whole sample) / 1947.2469_Gwh_b / 1947.2469_Gwh_c
			1947.2469Gwhnoincarea	analysis of area with no inclusions	see 1947.2469_Gwh_a (whole sample)
			1947.2469Gwhwhitinc	point analysis of inclusion	1947.2469_Gwh_d

47.2477, Egypt, XIX Dynasty

Provenance and Date: Listed separately as 1947.2477 A, B and C. All are from the Beck Collection and are from Egypt. B was excavated by G. Brunton in 1929 but the excavator is not mentioned for C. No specific sites are listed. All are dated to the XIX Dynasty. C is listed as long string of brown and yellow faience beads with a few yellow disc beads.

Notes: Mostly cylinder or barrel disc beads. One sample of yellow opaque glass was taken.

Notes (analytical): The composition of this sample renders it very bright when seen at the same brightness and contrast levels as normal for other samples, suggesting it has a very high Z composition. It contains numerous bubbles.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2477Cyell	yellow	Y	1947.2477Cyellmat1 1947.2477Cyellmat2	matrix averaged from 2 point analyses	1947.2477Cyell_a (whole sample) / 1947.2477Cyell_b / 1947.2477Cyell_c

32.421, Egypt, XVIII – XX Dynasties

Provenance and Date: Listed as 1932.421 A - B. A is string of small blue glass beads. B is cut cowrie shells. Source is Egypt Exploration Society, excavated by Egypt Exploration Society but no specific site given. Dated to between XVIII and XX Dynasties.

Notes: Bead. Green and opaque white. Length of two joined fragments is 13mm.

Notes (analytical): Sample contains two distinct areas present as streaks under the microscope. These were labelled a and b. Their width made it difficult to be certain a point analysis had not been affected by the close proximity of the other area, however.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
32.421AB	black	N	1932.421ABmat1 1932.421ABmat2	matrix averaged from 2 point analyses	1932.421AB_a (whole sample)

35.1153, Egypt, XVIII – XX Dynasties

Provenance and Date: Listed as string of early glass beads. Source is G. F. Rogers. Excavated in Egypt, though no specific site listed (collection). Beads dated between XVIII and XX Dynasties.

Notes: Contains small green and some blue short cylinder or disc beads. Dark blue / black with applied / mixed opaque yellow.

Notes (analytical): although some opaque areas were noted for this sample none could be identified using the microprobe, suggesting that the very small amounts of opaque material originally present had been lost to polishing.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
35.1153_	dark blue	N	1935.1153mat1 1935.1153mat2	matrix averaged from 2 point analyses	1935.1153_a (whole sample)

47.2499, Egypt, XXV Dynasty

Provenance and Date: Listed separately as 1947.2499 A, B, C, D, E, F and G. All are from the Beck Collection. Materials for all listed as faience and stone. All are from Egypt, dated to the XXVI Dynasty. Beck card is missing and none have details of specific site or excavator. D is listed as blue faience amulet.

Notes (analytical): it was impossible to take separate point readings over the inclusions in *Di* as they were in close proximity either to several holes or to the sample edge, rendering attempted readings too low in accuracy.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2499Di	white	Y	1947.2499Dimat1 1947.2499Dimat2	matrix averaged from 2 point analyses	1947.2499Di_a (whole sample) / 1947.2499Di_b / 1947.2499Di_c / 1947.2499Di_d and 1947.2499Di_e (high Z inclusions)
47.2499Dii	yellow	Y	1947.2499Diimat1 1947.2499Diimat2	matrix averaged from 2 point analyses	1947.2499Dii_f (whole sample) / 1947.2499Dii_g / 1947.2499Dii_h

35.1172, Egypt, 8th – 5th centuries B.C.

Provenance and Date: Listed as sting of blue glass beads and 'Etruscan' beads coloured by cobalt possibly mixed with copper. Source is G.F. Rogers. Excavated in Egypt. Dated between 8th and 5th centuries BC.

Notes: Dark blue bead, length 18mm. Weathered (weathering appears opaque yellow on photograph).

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
35.1172_	blue	N	1935.1172mat1 1935.1172mat2	matrix averaged from 2 point analyses	1935.1172_a (whole sample)

47.2553, Egypt, 1st millennium B.C.

Provenance and Date: Listed separately as 1947.2553 A and B. Both are from Beck Collection. Both from Egypt but period is uncertain, described as 'late'. Listed as consisting of glass, cowrie shell and shell. A is two bottle green glass eye beads with black and yellow eyes; B is string of small rough glass beads, one eye bead and a cowrie shell. Excavated by G. Brunton in 1929.

Notes: Sample is an opaque, bluish-white.

Notes (analytical): the sample contains a patch of low Z material, analysed separately as dkptch, and has no visible inclusions.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2553AB	white	Y	1947.2553ABmat1 1947.2553ABmat2	matrix averaged from 2 point analyses	1947.2553AB_a (whole sample) / 1947.2553AB_b / 1947.2553AB_c
			1947.2553ABdkptch	large low Z area with no visible inclusions	see 1947.2553AB_a (whole sample)

47.2208, Ur, c.900B.C.

Provenance and Date: Listed separately as 1947.208 A and B. A listed as string of glass beads; B listed as stone bead. A is 102 glass beads. Description: "eight blue glass beads, some segmented, and came with other objects from Mesopotamia." Thought to be Assyrian or Babylonian c.900BC. Source is Beck Collection.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2208A	blue	N	1947.2208Amat1 1947.2208Amat2	matrix averaged from 2 point analyses	n/a

47.2123, Ur, Iron Age (pre-600B.C.)

Provenance and Date: Museum collection lists two accessions for 1947.2123. Not dated but noted as probably before 600BC. From the Beck Collection, source date 1947. Listed as from Ur, 'prehistoric', excavated by Leonard Woolley in 1928 or 1929).

Notes: Only item *A* could be found in the collection. It is a black glass zoned bead with a white band. Due to the fragility of the band, it was decided to sample the black material only, from the edge of the thread-hole. Although it appears black under visual examination, its apparent opacity may be caused by the intensity of colouration.

Notes (analytical): The above note was supported by the analysis which revealed a homogeneous matrix with a few small bubbles, and only two small very high Z inclusions and a lower Z feature.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2123AB	black	N	47.2123ABImat1 47.2123ABImat2	matrix averaged from 2 point analyses	47.2123ABI (whole sample)
			47.2123ABIdkinc	point analysis of low Z feature	47.2123ABIa

47.2133, Ur, c.600B.C. (Nebuchadnezzar)

Provenance and Date: Listed separately as 1947.2133.1 (5 items); 1947.2133.2 (3 items); 1947.2133.3 (6 items): 1947.2133.4 (2 items); 1947.2133.5 (35 items). All are beads. Source is Beck Collection. All listed as Neobabylonian, excavated at Ur and dating to 600BC. Following is written for all, under 'context': "String of mixed glass beads (horned, zoned, etc.); yellow glass; green-black glass; agates; also fragments in bottle. Time of Nebuchadnezzar - 600BC. Excavated by Woolley, Sir Leonard in 1930 and 1931." All listed as in poor condition, requiring conservation. Individual descriptions:

Notes: Opaque turquoise, yellow and white: yellow, horned segmented bead with irregular knobs in profile and section; turquoise, yellow and yellowish green bands on ellipsoidal barrel bead with circular section; dark blue and white zoned bead, sub-spherical, circular section.

Notes (analytical): *i* has apparent mixing streaks, as opacifying particles present in these. Could possibly be a function of the way the sample was worked, or due to mixing which is interesting as it is white, but note that *i* is also very cracked, affecting results, and the cracks are also visible under the optical microscope. *ilowinc* is analysis of area with apparent lack of particulate inclusions, which may be useful in explaining what was mixed with the 'white' glass / opacified area. Although *ii* is a turquoise glass and appears to be opaque, very few, isolated inclusions only were found and not enough were present to take comparative images for image analysis.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2133i	white	Y	1947.2133imat1 1947.2133imat2	matrix averaged from 2 point analyses	1947.2133i_a (whole sample) / 1947.2133i_b / 1947.2133i_c
			1947.2133ilowinc	analysis of area with lower number of inclusions	see 1947.2133i_a (whole sample)
47.2133ii	turquoise	Y	1947.2133iimat1 1947.2133iimat2	matrix averaged from 2 point analyses	1947.2133ii_a (whole sample)
			1947.2133iiwhitinc	point analysis of inclusion	1947.2133ii_b

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2133iii	yellow	Y	1947.2133iiimat1 1947.2133iiimat2	matrix averaged from 2 point analyses	1947.2133iii_a (whole sample) / 1947.2133iii_b / 1947.2133iii_c
			1947.2133iiifeat	analysis of unusual feature	1947.2133iii_d
			1947.2133iiiwhitinc	point analysis of inclusion	1947.2133iii_e

47.2082, Ur, Neobabylonian or Persian

Provenance and Date: Listed as string of 16 beads ('glass; stone; agate'). Source is Beck Collection. Neobabylonian or Persian, excavated in Ur by Sir Leonard Woolley in 1925 or 1926.

Notes: Opaque yellow; opaque green.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2082_	yellow or green	Y	1947.2082mat1 1947.2082mat2	matrix averaged from 2 point analyses	1947.2082_a (whole sample) / 1947.2082_b / 1947.2082_c
			1947.2082whitinc1	point analysis of inclusion	1947.2082_d

47.2046, Ur, 8th – 6th centuries B.C.

Provenance and Date: Source is Beck Collection. Excavated by Sir Leonard Woolley in 1926.

Notes: Opaque yellow cylindrical eye bead (glass) with small 'black' streaks. Museum card description, possibly from Beck or Woolley himself: "eye bead of yellow glass made with 6 raised eyes of same colour, each wound into a small annular bead as applied. Small black marks in the glass on one side only. This type of bead is not known elsewhere to my knowledge."

Notes (analytical): two sets of analyses with same labels are included here, as analysis was undertaken of the same areas on two separate days, the first set not being entirely satisfactory (only one set is used in the data tables and production of PCA and bivariate plots, etc.). Note that the sample is opaque yellow but has two very thin, apparently black lines present, though these were too small to undergo separate analyses.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2046_	yellow	Y	1947.2046mat1 1947.2046mat2	matrix averaged from 2 point analyses	1947.2046_a (whole sample) / 1947.2082_b / 1947.2082_c
			1947.2046whitinc1	point analysis of inclusion	see 1947.2046_a (whole sample)
			1947.2046crys1	analysis of crystalline material	1947.2046_d

47.2087, Ur (Dikdikkah), 8th – 6th centuries B.C.

Provenance and Date: Listed as string of mixed glass beads. Includes broken eye bead, one black glass barrel bead, two green and yellow glass barrel beads. Source is Beck collection. Excavated at Ur (Dikdikkah) by Sir Leonard Woolley in 1925 or 1926.

Notes: Items listed as 2087 were stored separately as 1, 2, 3, 4, etc. For the present study 4 and 8 were sampled.

Notes (analytical): *4i* and *4ii* were two areas within sample *2087_4* which visually appears to be opaque white with a possible trace of 'black', but under the electron microprobe was found to comprise of two distinct areas, which were thus analysed separately. Note that the small size of this sample has probably negatively affected results, leading to a low overall percentage (89%), but attempt to re-run the analysis at a later date did not improve this.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2087_4i	black	N	1947.2087_4imat1 1947.2087_4imat2	matrix averaged from 2 point analyses	see 1947.2087_4_a (whole sample 4i and 4ii)
			1947.2087_4iwhitinc1	point analysis of inclusion	1947.2087_4i_b
47.2087_4ii	white	Y	1947.2087_4iimat1 1947.2087_4iimat2	matrix averaged from 2 point analyses	1947.2087_4_a (whole sample 4i and 4ii) / 1947.2087_4ii_c / 1947.2087_4ii_d
			1947.2087_4iiwhitinc2	point analysis of inclusion	1947.2087_4ii_e
47.2087_8i	yellow	Y	1947.2087_8imat1 1947.2087_8imat2	matrix averaged from 2 point analyses	1947.2087_8_a (whole sample 8i and 8ii) / 1947.2087_8i_b / 1947.2087_8i_c
47.2087_8ii	turquoise	Y	1947.2087_8iimat1 1947.2087_8iimat2	matrix averaged from 2 point analyses	1947.2087_8_a (whole sample 8i and 8ii) / 1947.2087_8ii_d / 1947.2087_8ii_e
			1947.2087_8iiwhitinc1	point analysis of inclusion	1947.2087_8ii_f
			1947.2087_8iiwhitinc2	point analysis of inclusion	1947.2087_8ii_g

47.1964, Cumae (Egyptian?), 14th century B.C.

Provenance and Date: Source is Beck Collection. Listed as from Cumae, Italy, suggested as 14th century BC in date and to be compared with XVIII Dynasty Egyptian beads (see the Bead Study Trust 1997, Catalogue of the Beck Collection Part 1: Europe, p. 82).

Notes: Glass spiral bead, black with a right hand flush yellow spiral. Ellipsoid form with collared ends.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.1964i	black	N	1947.1964imat1 1947.1964imat2	matrix averaged from 2 point analyses	see 1947.1964_a (whole sample including 64i and 64ii)
47.1964ii	yellow	Y	1947.1964iimat1 1947.1964iimat2	matrix averaged from 2 point analyses	1947.1964_a (whole sample including 64i and 64ii) / 1947.1964_b / 1947.1964_c

47.1965, Italy, 10th – 7th centuries B.C.

Provenance and Date: Listed as string of beads. Materials listed as coral(?); shell; glass; agate. Following description given: "String of 35 beads which has been split up by Mr. Beck into different types no. 296 A - L. They include three of coral, two of (?)shell, nine glass eye-beads, fifteen dark blue glass, four green glass and an agate seal of Persian shape with a representation of a rider on horseback, considered by Mr. Sidney Smith of the British Museum to be Mesopotamian work of 9 - 10 century BC. Mr. Beck said there were 53 beads. A second string of 16 beads with Mr. Beck's no. 296 has turned up. This brings the total to 51 (only two missing from the original total of 53). This second string includes three long barrel beads, brown with white wave which Mr. Beck compares to beads from Tzarros, Sardinia (7th century BC)." Source is Beck Collection, place is listed as "Europe; Italy: ?Sardinia ?Tzarros, date 10th - 7th century BC. The piece considered as Mesopotamian by Sidney Smith was not sampled.

Notes: *I* is apparently opaque white, though it is unclear from visual examination whether this is in fact an artefact of weathering. *II* appears to be black but this is probably caused by the presence of a very strong blue colour, most likely caused by cobalt.

Notes (analytical): *E23* combines analyses of areas labelled visually as yellow and turquoise: no clear distinction could be found under electron microprobe. Possible that yellow area is in fact weathering. Note, however, that *mat1* and *mat2* are from the area labelled as *'2'* and *mat3* from the area labelled as *'3'*. *E23gr* is lower Z area which may correspond to a different colour. *1965Cnoincl* is streak through sample which does not contain inclusions; note that most of this sample shows banding under microprobe, assumption is that this is result of mixing of yellow and blue glass used to form the turquoise shade. *Incrich* is most of sample, containing inclusions. Visually the entire samples appears to be opaque turquoise in colour, but may be mixed as suggested by area without inclusions. *JIII* is translucent but contains a small number of high Z inclusions, analysed as *whitinc* and *whitinc2*.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.1965I	white	?	47.1965Imat1 47.1965Imat2	matrix averaged from 2 point analyses	47.1965I (whole sample)
			47.1965Idkinc	point analysis of inclusion	47.1965Ia
			47.1965Iwhitinc	point analysis of inclusion	47.1965Ib
47.1965I23	black	N	47.1965I23mat1 47.1965I23mat2 47.1965I23mat3	matrix averaged from 3 point analyses	n/a
47.1965II	dark blue	N	47.1965IImat1 47.1965IImat2	matrix averaged from 2 point analyses	n/a
47.1965A	turquoise	Y	47.1965Amat1 47.1965Amat2	matrix averaged from 2 point analyses	47.1965A (whole sample) / 47.1965Ac / 47.1965Ad
			47.1965Altgr	analysis of area of matrix with different Z average	47.1965Aa / 47.1965Ab (possible holes)
			47.1965Awhitinc	point analysis of inclusion	47.1965Ae / 47.1965Af / 47.1965Ag
47.1965B1	white	Y	47.1965B1mat1 47.1965B1mat2	matrix averaged from 2 point analyses	47.1965B1 (whole sample) / 47.1965B1a / 47.1965B1b / 47.1965B1c (area of matrix with larger inclusions)
			47.1965B1whitinc	point analysis of inclusion	47.1965B1d
47.1965B2	turquoise	Y	47.1965B2mat1 47.1965B2mat2	matrix averaged from 2 point analyses	47.1965B2 (whole sample) / 47.1965B2a / 47.1965B2b
			47.1965B2whitinc	point analysis of inclusion	47.1965B2c
47.1965Cnoincl	blue	N	47.1965Cnoincla 47.1965Cnoinclb	matrix averaged from 2 point analyses	47.1965C (whole sample)
47.1965Cincrich	turquoise	Y	47.1965Cincrich1 47.1965Cincrich2	matrix averaged from 2 point analyses	47.1965Cb / 47.1965Cc
			1947.1965grinc	analysis of low Z crystalline inclusion	47.1965Cd
			47.1965Cwhitinc	point analysis of inclusion	47.1965Ce
			47.1965Clgcrys 47.1965Clgcrysb	analysis of area with low Z crystallite averaged from 2 point analyses	47.1965C (whole sample)

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.1965E1_	yellow	Y	47.1965E1mat1 47.1965E1mat2	matrix averaged from 2 point analyses	47.1965E1 (whole sample) / 47.1965E1c / 47.1965E1d
			47.1965E1inc1	point analysis of inclusion	47.1965E1a
			47.1965E1inc2	point analysis of inclusion	47.1965E1b
47.1965E23_			47.1965E23mat1 47.1965E23mat2	matrix averaged from 2 point analyses	47.1965E23 (whole sample) / 47.1965E23a / 47.1965E23b
47.1965E23gr	turquoise	Y	47.1965E23gr1	matrix averaged from 2 point analyses	see 47.1965E1 (whole sample) - 'light grey' anomaly
			47.1965E23gr2		
			47.1965E23dkgr	analysis of low Z crystalline inclusion	see 47.1965E1 (whole sample) - 'dark grey' anomaly
47.1965JI	blue	N	47.1965JImat1 47.1965JImat2	matrix averaged from 2 point analyses	n/a
47.1965JII	blue	N	47.1965JIImat1 47.1965JIImat2	matrix averaged from 2 point analyses	47.1965JIIa (to show weathering at sample edge)
47.1965JIII	dark green	N	47.1965JIIImat1 47.1965JIIImat2	matrix averaged from 2 point analyses	n/a
			47.1965JIIIwhitinc	point analysis of inclusion	47.1965JIIIa (two isolated white inclusions) / 47.1965JIIIb (whitinc)
			47.1965JIIIwhitinc2	point analysis of inclusion	
47.1965JIV	blue	N	47.1965JIVmat1 47.1965JIVmat2	matrix averaged from 2 point analyses	n/a
47.1965JV	blue	N	47.1965JVmat1 47.1965JVmat2	matrix averaged from 2 point analyses	n/a

47.2006, Rhodes (Cameiros), c. 900 B.C.

Provenance and Date: Listed separately as 1947.2006 A and B. A is glass; B faience. Both are listed as from Cameiros, Rhodes. Dated to c. 900 B.C. (see the Bead Study Trust 1997, Catalogue of the Beck Collection Part 1: Europe, p. 109 - 110); B listed as dating to 7th century BC. Source is Beck Collection.

Notes: Corroded black; corroded opaque yellow; light blue.

Notes (analytical): *Aii* and *Aiii* are not distinguished visually, but appear to consist of two separate areas under microprobe examination. It is therefore uncertain which, if not both, are opaque yellow as was assigned under visual examination in a sample fragment which also contained a colour of black appearance (*Abl*).

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2006Ai	black	N	1947.2006Aimat1 1947.2006Aimat2	matrix averaged from 2 point analyses	see 1947.2006A_a (whole sample including Ai and Aiii)
47.2006Aii	yellow	Y	1947.2006Aiimat1 1947.2006Aiimat2	matrix averaged from 2 point analyses	1947.2006A_a (whole sample including Ai and Aii) / 1947.2006Aii_a / 1947.2006Aii_b
47.2006Aiii	yellow	Y	1947.2006Aiiimat1 1947.2006Aiiimat2	matrix averaged from 2 point analyses	1947.2006A_a (whole sample including Aii and Aiii) / 1947.2006Aiii_a / 1947.2006Aiii_b
47.2006Abl	blue	N	1947.2006Ablmat1 1947.2006Ablmat2	matrix averaged from 2 point analyses	n/a

47.2002, Cyprus, 9th – 7th centuries B.C.

Provenance and Date: Source is Beck Collection. Four torc fragments listed seperately as 1947.2002 A, B, C and D. All are suggested as being Greek or Etruscan, and coming from Cyprus, 7th century BC or earlier. If - as thought - from separate torcs note that all fragments are nonetheless very similar in design. C and D are small segments with one bead attached to each. The two larger parts of the torc(s) (A and B) suggest that it / they can be dated to between 9th and 7th centuries BC due to similar finds in Cyprus and Sardinia which are thought to have been of Greek or Etruscan work (see the Bead Study Trust 1997, Catalogue of the Beck Collection Part 1: Europe, pp. 99 - 101).

Notes: Torc with glass beads. Item precious / fragile so only one sample taken. Not all described in card were present. Most beads are an aqua blue; one (sampled) is opaque white. The Beck card descriptions can be summarised thus: "(A) ?Silver torc or collar with hook ends, probably joined with a string. Beads include two crystal; one twisted square glass (clear); two melon beads (one cut spirally); one dark blue glass with red spots; three eye beads and seven glass beads of varying colour and size. (B) four of toric glass; two stratified eye beads; one amber glass melon bead; one translucent crystal; one ball bead of glazed clay and seven glass beads of different shapes and colours. (C) blue glass bead on terminal fastening. (D) amber bead on portion of silver torc."

Notes (analytical): particulate inclusions are present as streaks, suggesting that the opaque glass was not produced in a single-stage operation. The pattern formed by the streaks, however, may relate to working due to their formation of what appear on the sample present to be concentric arcs.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.2002_	white	Y	1947.2002mat1 1947.2002mat2	matrix averaged from 2 point analyses	1947.2002_a (whole sample) / 1947.2002_d / 1947.2002_e
			1947.2002dkptch1	point analysis of inclusion	1947.2002_c
			1947.2002whitinc1	point analysis of inclusion	1947.2002_b

47.1995, Crete, c.8th century B.C.

Provenance and Date: Listed as 3 segmented beads (glass; faience). Thought to be from Crete. Suggested date is 8th century BC (see the Bead Study Trust 1997, Catalogue of the Beck Collection Part 1: Europe, p. 98).

Notes: Sample exterior has been corroded to a powdery white.

Notes (analytical): sample contains streaks of a higher Z material, roughly corresponding with the location of inclusions, though it appears translucent. These are not distinct enough to label and analyse as separate areas, however, though it was possible to point analyse one of the larger inclusions as well as an unusual feature located in the area of the streaks. They are present in the centre of the sample and therefore do not appear to correspond with the weathering / corrosion on the exterior.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.1995_	light green	N	1947.1995mat1 1947.1995mat2	matrix averaged from 2 point analyses	1947.1995_a (whole sample) / 1947.1995_b / 1947.1995_c
			1947.1995whitinc1	point analysis of inclusion	1947.1995_d
			1947.1995feat	analysis of unusual feature	1947.1995_e

47.1999, Delos, 600 – 300 B.C.

Provenance and Date: Listed as glass pendant, Source is Beck Collection. Found on Delos, Greece. Pendant dates 600 - 300 BC on stylistic grounds (see the Bead Study Trust 1997, Catalogue of the Beck Collection Part 1: Europe, p. 121). Collected in 1931.

Notes: Pendant of brown, white and blue glass and a fragment of blue and white glass. Sample consists of two fragments, one opaque white and the other a translucent, purplish black.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
47.1999i	Black	N	1947.1999imat1 1947.1999imat2	matrix averaged from 2 point analyses	see 1947.1999_a (whole sample including 99i and 99ii)
47.1999ii	White	Y	1947.1999iimat1 1947.1999iimat2	matrix averaged from 2 point analyses	1947.1999_a (whole sample including 99i and 99ii) / 1947.1999iib / 1947.1999iic
			1947.1999iiwhitinc1	point analysis of inclusion	1947.1999ii_d

2. Samples from Tell Bazi and Deir 'Ain 'Abata

TBzII, Tell Bazi

Excavator's notes: 50/23 : 150 (05.04.--). Fragm. Pili (Prok) 50 / 23 50 tin pil, 2463.

Notes: Very weathered, milky yellow colour: difficult to assess original colour through visual examination. Sample consists of several fragments of this opaque material, possibly remains of beads due to shape of one fragment. Maximum dimension 7mm.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
TBz1II	?	?	TBz1IImat1 TBz1IImat2	matrix averaged from 2 point analyses	TBz1IIa (sample overview as whole sample too large for single x40 image)

TBzIV, Tell Bazi

Excavator's notes: 21 / 26 : 5. Glas fragm (Prox) wu 21/26 : 3.

Notes: Clear / milky nodule of glass, c.10mm maximum dimension. Slightly weathered on some surfaces.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
TBz2IV	Colourless (cloudy)	N	TBz2IVmat1 TBz2IVmat2 TBz2IVmat3	matrix averaged from 3 point analyses	TBz2IVa (whole sample) / TBz2IVb / TBz2IVc

TBzV, Tell Bazi

Excavator's notes: 31/33 : 3 (03.10.1996) blaus glaufindchem 31 / 33 N-W. Prode in Ramscluuctt.

Notes: Lump of (copper?) blue glass, weathered on one side (broken during excavation?). Max width 7mm.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
TBz2V	blue	N	TBz2Vmat1 TBz2Vmat2	matrix averaged from 2 point analyses	TBz2Va (whole sample) / TBz2Vb (unanalysed high Z patch)

DAAI, Deir 'Ain 'Abata

Notes: *2* is very weathered fragment of apparently turquoise glass, dimensions 4 x 3 x 2mm; *3* is slightly less weathered than other samples from Deir 'Ain 'Abata and is relatively homogeneous, maximum dimension is 5mm; *4* is quite weathered but it appears there are at least two colours of glass present in this fragment, maximum dimension is c.5mm.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
DAAI2	turquoise	Y	DAAI2mat1 DAAI2mat2	matrix averaged from 2 point analyses	DAAI2a (whole sample) / DAAI2b / DAAI2c
DAAI3	blue	N	DAAI3mat1 DAAI3mat2	matrix averaged from 2 point analyses	DAAI3a (whole sample)
DAAI4	?	?	DAAI4mat1	matrix averaged from 2 point analyses	DAAI4a (whole sample) / DAAI4b (whole sample)
			DAAI4mat2		
			DAAI4whi	analysis of area with higher Z	see DAAI4a and DAAI4b
			DAAI4dar	analysis of area with lower Z	see DAAI4a and DAAI4b

DAAII, Deir 'Ain 'Abata

Notes: Tiny fragment of blue glass, maximum dimensions c.3mm.

Details:

Sample Code	Colour	Opaque?	Analyses	Description of Analysis	List of Microprobe Images
DAAIIA	blue	N	DAAIIAmat1 DAAIIAmat2	matrix averaged from 2 point analyses	DAAIIAa (whole sample)

3. Samples Analysed with ToF-SIMS

Th267, Gymnasio Tomb 23, Thebes, Greece, 14th – 13th centuries B.C.

Sampler's notes: sample is opaque white decoration on polychrome bead. from Leivantes – Kokkinonyzes. T.I. – OM3. AK/Δ 5873d. KN B6 (Kalliopi Nikita, University of Nottingham).

Published References: full publication in preparation (Kalliopi Nikita).

Brak12, Tell Brak, c. 1300 B.C.

Sampler's notes: From an opaque turquoise ingot fragment. Tell Brak, Syria. Has been analysed by EPMA (Julian Henderson, University of Nottingham).

Published References: EPMA results in Henderson (1997, 96): sample Br9, Table 6b. Also analysed by TIMS at British Geological Survey, revealing a Sr and Nd isotope signature consistent with a Mesopotamian origin (Henderson et al. 2010): sample Brak-12.

Th153, Megalo Kastelli (cemetery), Thebes, Greece, c.1330 – 1190 B.C.

Sampler's notes: sample is opaque yellow decoration on 'Egyptian glass vessel' (fragment). Megalo Kastelli 23379. KN – R – 148. Late Helladic IIIB (Kalliopi Nikita, University of Nottingham).

Published References: full publication in preparation (Kalliopi Nikita).

Am2, Amarna, c.1350 - 1330 B.C.

Sampler's Notes: Polychrome glass bead. Analysed with EPMA (Chloë Duckworth, University of Nottingham).

Published References: previously unpublished. From Beck Collection of Beads, CUMAA (see online catalogue). See notes for 32.408 (I: opaque yellow) above.

Appendix 2
Tables of Results

See Appendix 1 for full details for all sample codes and spot analyses along with cross-references to the BSE images found in Appendix 4.

EPMA results are shown with matrix analyses averaged (number of matrix analyses taken for each sample can be found in Appendix 1).

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	4740	late 18th Dyn	vessel	dk blue	opq white	opq yell				3
Memphis	Cooney 1976	4741	late 18th - 19th Dyn	vessel	opq dk blue	opq white	opq yell	opq turq			4
Memphis	Cooney 1976	4742	late 18th Dyn	vessel	opq turq	dk blue	opq yell				3
Memphis	Cooney 1976	4743	late 18th Dyn	vessel	opq dk blue	opq yell	opq turq	opq white			4
Medinet Ghurab	Cooney 1976	26301	late 18th - 19th Dyn	vessel	dk blue	opq white	opq turq	opq yell	brown		5
El-Menshiya	Cooney 1976	36343	19th Dyn	vessel	opq blue	opq white	opq orange-yell				3
Thebes	Cooney 1976	36344	late 18th - 19th Dyn	vessel	opq dk blue	opq white	opq yell	opq orange-yell			4
Kahun	Cooney 1976	47983	late 18th Dyn	vessel	opq dk blue	opq yell	opq white				3
/	Cooney 1976	59244	18th Dyn (Amenophis II)	vessel	dk blue	opq white	opq yell				3
Amarna	Cooney 1976	63787	late 18th Dyn	vessel	blue	brown	opq white	opq yell	purple		5
Ehnasiya	Cooney 1976	64332	late 18th - 19th Dyn	vessel	opq dk blue	opq yell	opq turq	opq white			4
/	Cooney 1976	64333	late 18th - 19th Dyn	vessel	opq purple						1
/	Cooney 1976	64342	late 18th - 19th Dyn	vessel	blue	opq turq					2
Medinet Ghurab	Cooney 1976	67027	18th Dyn (Tutankhamun)	vessel	opq turq	opq white	opq yell	black			4
/	Cooney 1976	67064	late 18th Dyn	vessel	blue	opq white	opq yell	purple			4
Amarna	Cooney 1976	67065	late 18th Dyn (Akhenaten)	vessel	dk blue	opq white	opq yell				3
Medinet Ghurab	Cooney 1976	67395	late 18th Dyn	vessel	opq dk blue	opq yell	dk blue	opq white			4
/	Cooney 1976	2589	late 18th Dyn	vessel	dk blue	opq yell	opq white	turq			4
/	Cooney 1976	2590	late 18th Dyn	vessel	opq dk blue	opq yell	opq white				3
/	Cooney 1976	23063	late 18th Dyn (Amenophis III)	vessel	dk blue	opq yell	opq white				3

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
Nabesha	Cooney 1976	23616	late 18th Dyn	vessel	lt green	opq yell	opq white				3
/	Cooney 1976	24391	18th Dyn (Tuthmosis III)	vessel	opq turq	sheet gold					2
/	Cooney 1976	59246	late 18th Dyn	vessel	dk blue	opq yell	opq white				3
Thebes	Cooney 1976	64334	late 18th Dyn	vessel	dk blue	opq white	opq yell				3
/	Cooney 1976	64335	late 18th Dyn	vessel	blue	opq white	opq yell				3
/	Cooney 1976	29210	late 18th - 19th Dyn	vessel	lt green	black	white				3
Medinet Ghurab	Cooney 1976	37499	late 18th - 19th Dyn	vessel	opq purple	opq white	opq yell	opq turq			4
Thebes	Cooney 1976	1919	late 18th - 19th Dyn	vessel	opq white						1
Medinet Ghurab	Cooney 1976	64338	19th Dyn (Ramesses II)	vessel	purple	opq white	opq turq	opq yell	blue		5
Medinet Ghurab	Cooney 1976	64339	19th Dyn (Ramesses II)	vessel	opq turq	black	opq white	opq yell	black		5
Medinet Ghurab	Cooney 1976	65661	late 18th Dyn	vessel	black	grey-green	opq white	opq yell			4
Medinet Ghurab	Cooney 1976	67026	late 18th Dyn	vessel	opq dk blue	opq white					2
Amarna	Cooney 1976	36282	18th Dyn (Amenophis III)	vessel	black	opq yell	opq white				3
Mostagedda	Cooney 1976	62531	late 18th - 19th Dyn	vessel	opq dk blue	opq white	opq yell				3
/	Cooney 1976	67081	late 18th - 19th Dyn	vessel	opq dk blue	opq white	opq yell	turq			4
Memphis	Cooney 1976	4739	18th Dyn (Amenophis III)	vessel	dk blue	opq white	black	opq yell	lt blue	turq	6
/	Cooney 1976	63785	18th Dyn	vessel	lt blue						1
/	Cooney 1976	64175	18th Dyn	vessel	opq green	black	opq white	opq yell	dark blue		5
/	Cooney 1976	64377	18th - 19th Dyn	vessel	dk blue						1
/	Von Saldern 1968	Carter 18.270	1400 - 1300	vessel	blue	opq white	opq yell				3

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Caron and Zoïtopoúlou 2008	1953.Dg.3	1400 - 1300	vessel	dk blue	opq white	opq yell	lt blue			4
Amarna	Harden 1979	CM I	1400 - 1350	vessel	black	opq white	opq yell				3
/	Harden 1979	CM II	1380 - 1350	vessel	opq blue	opq yell	opq white	green			4
Saqqara	Riefstahl 1986	37.340E	late 18th Dyn	vessel	dk blue	opq yell	opq white				3
Saqqara	Riefstahl 1986	37.341E	late 18th Dyn	vessel	dk blue	opq yell	opq white				3
/	Lilyquist and Brill 1993	Brooklyn 53.176.4	18th Dyn (Tuthmosis III)	vessel	opq turq	opq yell	black				3
Wadi Qirud	Lilyquist and Brill 1993	MMA 23.9	18th Dyn (Tuthmosis III)	vessel	opq turq						1
/	Lilyquist and Brill 1993	MMA 16.7.9	18th Dyn (Amenhotep II)	vessel	opq white	brown	opq turq				3
/	Lilyquist and Brill 1993	MMA 26.7.1150d	18th Dyn (Amenhotep II)	vessel	opq white	brown	opq blue				3
/	Lilyquist and Brill 1993	MMA 26.7.1163	18th Dyn (Amenhotep II)	vessel	opq red	opq turq	opq yell	dk blue	opq white		5
/	Lilyquist and Brill 1993	MMA 26.7.1164	18th Dyn (Amenhotep II)	vessel	opq red	dk blue	opq turq	opq yell	opq white		5
/	Lilyquist and Brill 1993	MMA 26.7.1165	18th Dyn (Amenhotep II)	vessel	dk blue	opq turq	opq yell				3
/	Lilyquist and Brill 1993	MMA 26.7.1169	18th Dyn (Amenhotep II)	vessel	purple						1
/	Lilyquist and Brill 1993	MMA 30.8.44a	18th Dyn (Tuthmosis IV)	vessel	opq turq	opq white	opq yell	opq blue			4
/	Tatton-Brown and Andrews 1991	EA 22819	1352 - 1336	vessel	dk blue	lt blue	opq yell				3
/	Tatton-Brown and Andrews 1991	EA 47620	c.1425	vessel	lt blue	opq yell	opq white	blue			4

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Tatton-Brown and Andrews 1991	EA 55193	1352 - 1336	vessel	blue	opq white	opq yell	dk blue			4
Amarna	Tatton-Brown and Andrews 1991	EA 64333	1330 - 1200	vessel	purple						1
Memphis	Tatton-Brown and Andrews 1991	EA 4741	1390 - 1352	vessel	dk blue	opq yell	opq white	opq turq			4
/	Tatton-Brown and Andrews 1991	EA 64342	1390 - 1352	vessel	blue	opq turq					2
Faiyum	Tatton-Brown and Andrews 1991	EA 47983	1390 - 1336	vessel	dk blue	opq yell	opq white				3
Memphis	Tatton-Brown and Andrews 1991	EA 4742	1390 - 1352	vessel	lt blue	dk blue	opq yell				3
Memphis	Tatton-Brown and Andrews 1991	EA 4743	1390 - 1336	vessel	dk blue	opq yell	opq turq	opq white			4
/	Tatton-Brown and Andrews 1991	EA 29210	18th - 19th Dyn	vessel	semi-trans white	black	opq white				3
Medinet Ghurab	Tatton-Brown and Andrews 1991	EA 64338	19th Dyn (Ramesses II)	vessel	brown	opq white	opq yell	opq turq			4
/	Tatton-Brown and Andrews 1991	EA 64335	18th - 19th Dyn	vessel	blue	opq yell	opq white				3
/	Tatton-Brown and Andrews 1991	EA 64334	1390 - 1336	vessel	black	opq white	opq yell				3
/	Tatton-Brown and Andrews 1991	EA 4749	1400 - 1300	vessel	dk blue	opq yell	opq white	opq turq			4
Malkata	Tatton-Brown and Andrews 1991	EA 27727	1390 - 1352	vessel	red	opq white	lt blue	opq yell			4
Amarna	Tatton-Brown and Andrews 1991	EA 68391	1352 - 1336	vessel	opq yell	dk blue	opq white				3

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Table 1

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
Thebes	Tatton-Brown and Andrews 1991	EA 68388	c.1400	vessel	opq turq	red	opq yell	opq white			4
Thebes	Tatton-Brown and Andrews 1991	EA 64125	c.1400	vessel	blue	opq white	opq yell	black			4
Amarna	Tatton-Brown and Andrews 1991	EA 64124	1352 - 1336	vessel	opq green	opq yell	opq white	opq blue	black		5
Amarna	Tatton-Brown and Andrews 1991	EA 64163	1352 - 1336	vessel	opq white	black	red				3
Amarna	Tatton-Brown and Andrews 1991	EA 68394	1352 - 1336	vessel	opq blue	dk blue	opq white				3
Amarna	Tatton-Brown and Andrews 1991	EA 65660	1352 - 1336	vessel	opq white	dk blue					2
Amarna	Tatton-Brown and Andrews 1991	EA 68398	1352 - 1336	vessel	opq white	dk blue	opq turq				3
/	Tatton-Brown and Andrews 1991	EA 24391	1457 - 1425	vessel	opq turq	gold leaf					2
Abydos	Nicholson 1993	Pilkington 1972/16	Late 18th Dyn	vessel	dk blue	opq turq	opq yell	opq white			4
Amarna	Nicholson 1993	EES obj. 21221	18th Dyn	vessel	dk blue	opq white	opq yell	opq turq	brown		5
/	Nicholson 1993	Munich AS 630	Late 18th Dyn	vessel	opq turq	opq yell	dk blue				3
/	Nicholson 1993	UC 22081	18th - 19th Dyn	vessel	dk blue	black	opq white	opq yell			4
/	Cooney 1976	6245-	18th - 19th Dyn	amulet	opq black	opq red	opq white				3
/	Cooney 1976	64118-	18th Dyn	amulet	opq black	opq white	opq red				3
Memphis	Cooney 1976	6258-	Late 18th Dyn	amulet	lt blue	opq yell	opq white				3
/	Cooney 1976	6259-	Late 18th Dyn	amulet	opq brown	opq white	opq yell				3
Memphis	Cooney 1976	6260-	Late 18th Dyn	amulet	opq dk blue	opq yell	opq white				3
/	Cooney 1976	6261-	Late 18th Dyn	amulet	opq black	opq white	opq red				3
/	Cooney 1976	6262-	Late 18th Dyn	amulet	opq black	opq white					2
/	Cooney 1976	8128-	Late 18th Dyn	amulet	turq						1

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Table 1

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	16430-	Late 18th Dyn	amulet	opq white	dk blue	opq black	lt blue			4
/	Cooney 1976	20887-	18th Dyn	amulet	dk blue	opq yell	opq white				3
/	Cooney 1976	29265-	Late 18th Dyn	amulet	opq black	brown	opq white	dk green			4
/	Cooney 1976	29266-	18th Dyn	amulet	dk blue	opq white	opq yell				3
/	Cooney 1976	64116-	18th Dyn	amulet	opq dk blue	opq white	opq yell				3
/	Cooney 1976	64179-	Late 18th Dyn	amulet	opq yell	turq	dk blue	opq white			4
/	Cooney 1976	64181-	Late 18th Dyn	amulet	opq dk blue	opq yell	opq white				3
/	Cooney 1976	64183-	Late 18th Dyn	amulet	opq turq	dk blue					2
/	Cooney 1976	64201-	Late 18th - 19th Dyn	amulet	opq lt red						1
Saqqara	Cooney 1976	64298-	Late 18th Dyn	amulet	opq dk blue	opq white	opq yell				3
/	Cooney 1976	65327-	Late 18th Dyn	amulet	opq turq	black	opq yell				3
/	Cooney 1976	65542-	Late 18th Dyn	amulet	opq dk blue	opq yell	opq white				3
/	Cooney 1976	65543-	Late 18th Dyn	amulet	opq dk blue	opq yell	opq white				3
/	Cooney 1976	65544-	Late 18th Dyn	amulet	opq dk blue	opq white	opq yell	turq			4
/	Cooney 1976	65545-	Late 18th Dyn	amulet	opq dk blue	opq lt blue	opq white				3
/	Cooney 1976	65546-	Late 18th Dyn	amulet	opq black	turq					2
/	Cooney 1976	65547-	Late 18th Dyn	amulet	opq dk blue	opq red	opq white				3
Amarna	Cooney 1976	67066-	18th Dyn (Akhenaten)	amulet	opq lt blue						1
/	Cooney 1976	13451-	18th Dyn	amulet	opq blue						1
/	Cooney 1976	20623-	Late 18th - 19th Dyn	amulet	opq blue						1
Thebes	Cooney 1976	54917-	Late 18th Dyn (Amenophis III)	amulet	dk blue						1
Memphis	Cooney 1976	16448-	18th Dyn	bead	dk blue	opq white	opq yell				3
Memphis	Cooney 1976	16449-	18th Dyn	bead	dk blue	opq white	opq yell				3
/	Cooney 1976	16338-	18th Dyn	gaming piece	opq dk blue						1

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	16339-	18th Dyn	gaming piece	opq dk blue						1
/	Cooney 1976	16538-	18th Dyn	gaming piece	opq black	opq white					2
/	Cooney 1976	16621-	18th Dyn	gaming piece	yellow						1
Tell el-Yahudiya	Cooney 1976	16891-	18th Dyn	gaming piece	opq blue						1
Amarna	Cooney 1976	55188-	18th Dyn	gaming piece	opq dk blue						1
/	Cooney 1976	55235-	18th Dyn	gaming piece	lt green	opq white	opq yell				3
/	Cooney 1976	64173-	18th Dyn	gaming piece	opq dk blue						1
/	Cooney 1976	64182-	18th Dyn	gaming piece	opq dk blue	opq yell					2
/	Cooney 1976	64310-	18th Dyn	gaming piece	dk blue						1
/	Cooney 1976	64311-	18th Dyn	gaming piece	opq lt blue						1
/	Cooney 1976	64312-	18th Dyn	gaming piece	lt blue						1
Amarna	Cooney 1976	57511-	Late 18th Dyn	jewellery misc	opq lt green	black	opq white	lt green			4
/	Cooney 1976	2847-	18th Dyn	jewellery misc	opq white						1
/	Cooney 1976	2851-	18th Dyn	jewellery misc	opq green						1

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	2854-	18th Dyn	jewellery misc	dk blue	opq yell					2
/	Cooney 1976	2855-	18th Dyn	jewellery misc	dk blue	opq yell					2
/	Cooney 1976	6270-	Late 18th Dyn	jewellery misc	opq green						1
/	Cooney 1976	16444-	Late 18th Dyn	jewellery misc	opq dk blue	opq yell	opq white				3
/	Cooney 1976	35991-	Late 18th Dyn	jewellery misc	dk blue	opq yell	opq white				3
/	Cooney 1976	67968-	Late 18th Dyn	jewellery misc	dk blue	opq yell	opq white				3
/	Cooney 1976	16442-	Late 18th Dyn	jewellery misc	blue	opq white					2
Memphis	Cooney 1976	16443-	18th Dyn (Amenophis III)	jewellery misc	opq white	dk blue	lt green				3
Memphis	Cooney 1976	16445-	18th Dyn (Amenophis III)	jewellery misc	opq yell	black	opq white				3
Memphis	Cooney 1976	16446-	Late 18th Dyn	jewellery misc	dk blue	opq yell	opq white				3
/	Cooney 1976	16541-	Late 18th Dyn	jewellery misc	opq dk blue	opq white	opq yell				3
/	Cooney 1976	20885-	18th Dyn	jewellery misc	lt green						1
/	Cooney 1976	29053-	Late 18th Dyn	jewellery misc	opq red						1
/	Cooney 1976	29255-	18th - 19th Dyn	jewellery misc	opq dk blue	dk green					2

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	29256-	18th - 19th Dyn	jewellery misc	opq dk blue	dk green					2
/	Cooney 1976	29257-	18th - 19th Dyn	jewellery misc	opq dk blue	opq yell					2
/	Cooney 1976	29258-	18th - 19th Dyn	jewellery misc	opq black	opq white	opq yell				3
/	Cooney 1976	29259-	18th - 19th Dyn	jewellery misc	opq dk blue	opq white	opq yell				3
/	Cooney 1976	29260-	18th - 19th Dyn	jewellery misc	opq dk blue	opq white	opq yell				3
/	Cooney 1976	29261-	18th - 19th Dyn	jewellery misc	opq dk blue	opq white	opq yell				3
/	Cooney 1976	29262-	18th - 19th Dyn	jewellery misc	opq dk blue	opq white					2
/	Cooney 1976	29263-	18th - 19th Dyn	jewellery misc	opq dk blue	opq yell					2
/	Cooney 1976	29264-	18th - 19th Dyn	jewellery misc	dk blue	opq white	opq yell				3
/	Cooney 1976	29268-	18th - 19th Dyn	jewellery misc	black	opq white					2
/	Cooney 1976	29269-	18th - 19th Dyn	jewellery misc	dk blue	opq white					2
/	Cooney 1976	29270-	18th - 19th Dyn	jewellery misc	dk blue	opq white					2
/	Cooney 1976	14508-	18th Dyn	jewellery misc	opq dk blue	opq white	dk blue	gold wire			4
/	Cooney 1976	16441-	18th Dyn	jewellery misc	opq dk blue	dk blue	opq white				3

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Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	37535-	Late 18th Dyn	jewellery misc	opq white						1
Amarna	Cooney 1976	55158-	Late 18th Dyn (Akhenaten)	jewellery misc	lt green						1
Amarna	Cooney 1976	57513-	Late 18th Dyn (Akhenaten)	jewellery misc	lt blue						1
Amarna	Cooney 1976	57514-	Late 18th Dyn	jewellery misc	opq white	black					2
Amarna	Cooney 1976	57515-	Late 18th Dyn	jewellery misc	opq white	lt purple					2
Amarna	Cooney 1976	57516-	Late 18th Dyn	jewellery misc	lt green						1
Amarna	Cooney 1976	58818-	Late 18th Dyn (Akhenaten)	jewellery misc	white						1
Amarna	Cooney 1976	58819-	Late 18th Dyn (Akhenaten)	jewellery misc	trans						1
Amarna	Cooney 1976	59322-	Late 18th Dyn (Akhenaten)	jewellery misc	opq white	black					2
Mostagedda	Cooney 1976	63347-	18th Dyn	jewellery misc	opq turq	dk brown					2
/	Cooney 1976	64297-	18th Dyn	jewellery misc	turq	opq white	purple				3
/	Cooney 1976	64303-	18th Dyn	jewellery misc	white						1
/	Cooney 1976	64304-	Late 18th Dyn	jewellery misc	opq white						1
/	Cooney 1976	64305-	Late 18th Dyn	jewellery misc	purple						1
/	Cooney 1976	65535-	Late 18th Dyn	jewellery misc	opq turq	opq yell					2

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	65536-	Late 18th Dyn	jewellery misc	opq turq	opq yell					2
/	Cooney 1976	66903-	18th Dyn	jewellery misc	lt blue	opq white	opq yell	opq dk blue			4
/	Cooney 1976	68496-	18th Dyn	jewellery misc	opq red	opq white					2
/	Cooney 1976	2895-	Late 18th Dyn (Amenophis III)	jewellery misc	opq turq	opq yell					2
/	Cooney 1976	48064-	Late 18th Dyn (Amenophis III)	jewellery misc	opq turq	opq yell					2
Thebes	Cooney 1976	6272-	Late 18th Dyn (Amenophis III)	jewellery misc	opq yell	blue	opq white				3
Thebes	Cooney 1976	6300-	Late 18th Dyn	jewellery misc	opq white	opq blue	blue				3
Thebes	Cooney 1976	16960-	18th Dyn	jewellery misc	opq white	black					2
/	Cooney 1976	16961-	18th Dyn	jewellery misc	opq turq	opq yell	dk blue				3
/	Cooney 1976	17041-	18th Dyn	jewellery misc	opq white	opq blue					2
/	Cooney 1976	21943-	18th Dyn	jewellery misc	lt blue	opq yell	dk blue	green			4
/	Cooney 1976	54933-	18th Dyn	jewellery misc	opq turq						1
/	Cooney 1976	54934-	18th Dyn	jewellery misc	lt blue						1
/	Cooney 1976	64185-	18th Dyn	jewellery misc	opq black	opq yell					2

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Cooney 1976	64186-	18th Dyn	jewellery misc	opq yell	opq white	lt blue				3
/	Cooney 1976	20888-	18th Dyn	jewellery misc	lt blue						1
Medinet Ghurab	Cooney 1976	67740-	18th Dyn	jewellery misc	opq dk blue						1
Medinet Ghurab	Cooney 1976	67769-	18th Dyn	jewellery misc	opq turq						1
Amarna	Cooney 1976	67806-	18th Dyn	jewellery misc	lt blue						1
Amarna	Cooney 1976	67959-	18th Dyn (Akhenaten)	jewellery misc	lt blue						1
Amarna	Cooney 1976	67960-	18th Dyn (Akhenaten)	jewellery misc	blue						1
Amarna	Cooney 1976	67962-	18th Dyn (Akhenaten)	jewellery misc	dk blue						1
Amarna	Cooney 1976	67963-	18th Dyn (Akhenaten)	jewellery misc	purple						1
Amarna	Cooney 1976	68476-	18th Dyn (Akhenaten)	jewellery misc	purple						1
Amarna	Cooney 1976	68476-	18th Dyn (Akhenaten)	jewellery misc	dk blue						1
Amarna	Cooney 1976	68476-	18th Dyn (Akhenaten)	jewellery misc	turq						1
Amarna	Cooney 1976	68476-	18th Dyn (Akhenaten)	jewellery misc	blue						1
Amarna	Cooney 1976	68476-	18th Dyn (Akhenaten)	jewellery misc	green						1

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
Amarna	Cooney 1976	68476-	18th Dyn (Akhenaten)	jewellery misc	opq yell						1
Amarna	Cooney 1976	68468-	18th Dyn (Akhenaten)	jewellery misc	lt blue						1
Amarna	Cooney 1976	68468-	18th Dyn (Akhenaten)	jewellery misc	opq turq						1
Amarna	Cooney 1976	68469-	18th Dyn (Akhenaten)	jewellery misc	opq dk blue						1
Amarna	Cooney 1976	68470-	18th Dyn (Akhenaten)	jewellery misc	opq dk blue						1
/	Tatton-Brown and Andrews 1991	EA 64335	18th - 19th Dyn	applicator	blue						1
/	Tatton-Brown and Andrews 1991	EA 64186	1375 - 1150	pendant	opq yell	opq white	blue				3
/	Tatton-Brown and Andrews 1991	EA 64297	1375 - 1150	pendant	blue	opq white	dk blue				3
/	Tatton-Brown and Andrews 1991	EA 2895	1375 - 1150	pendant	opq turq	opq yell	dk blue				3
/	Tatton-Brown and Andrews 1991	EA 64162	1375 - 1150	earplug	green	black	opq yell	opq white	opq turq		5
/	Tatton-Brown and Andrews 1991	EA 65535	1375 - 1150	earplug	blue	opq yell					2
/	Tatton-Brown and Andrews 1991	EA 29258	1375 - 1150	pendant	black	opq white	opq yell				3
/	Tatton-Brown and Andrews 1991	EA 29264	1375 - 1150	pendant	black	opq white	opq yell				3
/	Tatton-Brown and Andrews 1991	EA 63347	1375 - 1150	earring	dk blue	lt blue					2

Appendix 2
Table 1

Table of Colour Categorisation of LBA Egyptian Glass from Published Catalogues

Site / Source	Publication	Identification	Dates	Object	Base Colour	Colour 2	Colour 3	Colour 4	Colour 5	Colour 6	No. of Colours
/	Tatton-Brown and Andrews 1991	EA 68531	1375 - 1150	earplug	opq blue	opq white	opq yell				3
/	Tatton-Brown and Andrews 1991	EA 16443	1375 - 1150	earplug	dk blue	opq white	green				3
/	Tatton-Brown and Andrews 1991	EA 65544	18th Dyn	amulet	dk blue	opq white	opq turq				3
/	Tatton-Brown and Andrews 1991	EA 6261	18th Dyn	amulet	dk blue	red	opq white				3

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2	
1	32.385_	17.78	0	0.846	64.97	0.0015	0.0625	0	0.005	7.53	0.8275	0.0045	0.045	0.014	0	0	
2	32.385I	18.49	0.127	0.808	63.08	0.021	0.056	0	0.074	7.07	2.97	0.107	0.048	0.026	0.006	0	
3	32.385II	16.82	0.067	2.495	60.625	1.36	0.02	0	0	8.02	0.5885	0.004	0.919	0.0395	0.009	0	
	32.385IIwhitinc	13.81	0.032	1.169	31.74	0.684	0	0	0	8.89	0.292	0.008	43.45	0.869	0	0	
4	32.385IV	21.195	0.567	0.8145	60.98	0.1555	0.1005	0	0.06	4.99	4.48	0.075	0.8185	0.022	0.003	0	
	32.385IVwhitinc	20.69	0.416	0.694	50.49	0.153	0.052	0	0.039	5.98	3.54	0.076	16.42	0.335	0	0	
5	32.385V	14.95	0.038	2.23	63.24	0.646	0.0465	0	0	9.27	0.7065	0.0075	0.289	0.033	0	0	
	32.385Vwhitinc	11.98	0.844	1.4	40.61	0.413	0.016	0	0	5.6	0.532	0	13.84	0.235	0	0	
6	32.385VI	13.675	0.0065	2.59	63.38	2.525	0.094	0	0	8.57	1.064	0.007	0.1535	0.022	0.0015	0	
7	32.385VII	12.615	0.003	2.17	64.635	0.793	0.0315	0	0.0065	9.295	0.627	0.0035	1.655	0.096	0.0015	0	
	32.385VIIwhitinc	7.13	0.002	1.116	39.07	0.444	0.014	0	0	15.08	0.405	0	34.27	0.655	0.007	0	
8	32.385VIII	19.07	0	2.54	60.435	0.4925	0.0255	0	0.013	8.255	0.5965	0	1.025	0.0425	0.0045	0	
9	32.385IX	17.595	0.002	2.535	64.19	1.1445	0.027	0	0.0145	6.37	0.458	0	0.204	0.0435	0.0015	0	
10	32.385X	17.83	0.003	2.44	64.195	0.9175	0.0305	0.0035	0.0115	6.575	0.866	0	0.207	0.018	0.0035	0	
	32.385Xbrinc	15.61	0	1.95	57.97	0.808	0.017	0	0	5.36	0.689	0	0.13	0.012	0.003	0	
11	32.385X2	17.81	0.0005	2.435	64.375	0.9185	0.0335	0	0.0025	6.565	0.855	0	0.241	0.027	0.003	0	
	32.385X2lgwhitinc	3.28	0	0.529	10.59	0.268	0	0	0.01	0.907	0.137	0.101	1.092	0.036	0	0	
12	32.385XI	16.795	0.099	0.9825	67.075	0.5305	0.059	0	0.0655	6.21	1.461	0.0715	0.078	0.003	0.002	0	
	32.385XIgwhitinc	4.6	0	0.331	7.92	0.261	0	0	0.011	0.54	0.252	0.126	0.803	0.06	0.002	0	
13	32.385XII	18.61	0.1915	0.412	64.535	0.01	0.037	0	0.084	6.065	2.57	0.1405	0.101	0.018	0.002	0	
14	32.385XIII	16.69	0.0475	2.1	62.09	2.04	0.0145	0	0.003	7.265	0.4515	0.0055	0.56	0.0535	0	0	
	32.385XIIIwhitinc1	14.71	0.354	1.68	52.86	1.85	0.018	0	0.009	7.71	0.412	0	4.1	0.219	0.008	0	
	32.385XIIIwhitinc2	15.97	0.168	1.88	55.79	1.86	0.006	0	0	6.68	0.389	0	3.68	0.083	0	0	
15	32.385XIV	18.515	0.047	3.055	62.24	1.091	0.002	0	0.0195	4.525	0.573	0.0035	0.3415	0.0255	0	0	
	32.385XIVgwhitinc	0.534	2.37	0.057	5.22	0.328	0	0	0.007	0.478	0.025	0	33.42	0.48	0	0	
	32.385XIVwhitinc	13.19	0.286	2.3	47.48	0.784	0	0	0.033	3.3	0.453	0	9.2	0.109	0	0	
	32.385XIVdkpatch	0.887	0.032	2.42	69.7	1.68	0.015	0	0	4.77	0.621	0	0.159	0.044	0.003	0	
16	32.385XV	16.055	0.138	1.38	62.735	0.3325	0.1195	0	0.059	8.355	2.325	0.0925	0.388	0.031	0.002	0	
	32.385XV	19.435	0.0065	2.335	57.965	0.579	0.016	0	0	6.475	0.5305	0.0005	3.255	0.1305	0.0055	0	
	32.385XVinc	18.73	0	1.9	51.07	0.477	0.036	0	0	9.78	0.396	0	11.48	0.229	0	0	
17	32.385XX	7.195	0.013	1.695	83.795	3.665	0	0	0.001	1.762	0.0255	0.001	0.116	0	0.0025	0	
	32.385XXdk	0	0	0.01	97.5	0.188	0	0	0.009	0.002	0	0.007	0	0	0	0	

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
1	**32.385_**	3.95	0.404	0.24	0.5455	0.026	0	0	0	0	0.0065	0.075	97.333
2	**32.385I**	3.74	0.488	0.26	0.75	0.189	0.02	0	0	0	0	0.053	98.383
3	**32.385II**	4.285	0.354	0.4385	0.4715	0.022	0	0	0	1.103	0.001	0.125	97.766
	32.385IIwhitinc	2.79	0.213	0.131	0.218	0.005	0	0	0.077	0.422	0	0.04	104.84
4	**32.385IV**	3.165	0.629	0.4155	0.41	0.154	0.0145	0	0	0.015	0.0095	0.0795	99.153
	32.385IVwhitinc	2.92	0.569	0.344	0.563	0.123	0.017	0.031	0	0	0	0.064	103.52
5	**32.385V**	4.265	0.3835	0.2365	0.399	0.0195	0.008	0.0035	0.0005	0.362	0.012	0.154	97.301
	32.385Vwhitinc	3.12	1.065	0.171	0.371	0.027	0.076	0	0.034	23.42	0.032	0.085	103.87
6	**32.385VI**	4.165	0.532	0.3445	0.471	0.0235	0	0	0	0	0	0.1535	97.779
7	**32.385VII**	4.445	0.342	0.3445	0.457	0.013	0.0155	0	0	0.0135	0.009	0.1415	97.711
	32.385VIIwhitinc	2.94	0.241	0.182	0.141	0.02	0	0	0.072	0	0.026	0.175	101.99
8	**32.385VIII**	4.515	0.311	0.332	0.0445	0.023	0.024	0.002	0	0.007	0	0.1845	97.944
9	**32.385IX**	3.57	0.3185	0.42	0.3225	0.0135	0.0225	0	0	0.579	0.002	0.221	98.054
10	**32.385X**	3.315	0.4845	0.3135	0.6625	0.027	0.0075	0.0015	0	0.211	0.001	0.1345	98.258
	32.385Xbrinc	2.67	0.382	0.264	0.023	0.018	12.45	0	0	0.132	0	0.111	98.599
11	**32.385X2**	3.325	0.2485	0.322	0.3875	0.007	0.0235	0.0105	0	0.2625	0.0005	0.1595	98.011
	32.385X2lgwhitinc	0.326	0	0.128	0.1	0.013	0	0	0	0.155	0.021	0.027	17.72
12	**32.385XI**	3.295	0.4245	0.33	0.7935	0.1105	0.0105	0.0075	0	0.0105	0.015	0.1135	98.541
	32.385XIgwhitinc	0.195	75.33	0.23	0.044	0.281	0	0.01	0	0.504	0.037	0	91.536
13	**32.385XII**	3.92	0.4045	0.1525	0.953	0.252	0	0	0	0.0175	0.005	0.0705	98.552
14	**32.385XIII**	3.85	0.3315	0.298	0.918	0.023	0.013	0.008	0	1.615	0.0115	0.177	98.566
	32.385XIIIwhitinc1	4.18	1.56	0.287	0.956	0.015	0.017	0	0.015	8.32	0.012	0.155	99.446
	32.385XIIIwhitinc2	3.81	0.809	0.271	0.851	0.023	0.014	0	0	7.79	0	0.132	100.21
15	**32.385XIV**	4.705	0.3815	0.357	0.2645	0.012	0.0195	0	0	2.045	0	0.1845	98.407
	32.385XIVgwhitinc	0.331	0.359	0.071	0.108	0	0.026	0.008	0.046	48.95	0	0.303	93.121
	32.385XIVwhitinc	3.73	1.192	0.337	0.537	0.038	0.052	0	0	17.79	0	0.111	100.92
	32.385XIVdkpatch	4.4	0.396	0.366	0.729	0.035	0	0.019	0	0.778	0.053	0.203	87.31
16	**32.385XV**	3.675	0.715	0.295	0.5075	0.1565	0.007	0	0	0.0545	0.0155	0.141	97.58
	32.385XV	7.015	0.269	0.457	0.5865	0.012	0.003	0.003	0.006	0.004	0.0035	0.1155	99.208
	32.385XVIinc	6.29	0.193	0.448	0.548	0.004	0.031	0.009	0.071	0.008	0.011	0.108	101.82
17	**32.385XX**	0	0.0805	0.0205	0.2515	0	0.0095	0.0115	0	0.0005	0.007	0.084	98.737
	32.385XXdk	0	0	0	0.021	0.005	0	0	0	0	0.007	0.012	97.76

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2
17 (cont.)	32.385XXlt	0.893	0.023	2.07	69.97	13.81	0	0.009	0	2.09	0.06	0	0.104	0	0.001	0
	32.385XXwhitinc	6.88	0.001	1.26	80.16	2.92	0	0	0	1.357	0.031	0	0	0	0.002	9.14
18	27.1495All	17.97	0.2775	1.0335	66.865	0.001	0.122	0	0.063	4.375	2.475	0.121	0.1025	0.0095	0.0035	0
	27.1495IIIwhitinc	0.034	0.025	0.043	83.65	0.01	0.051	0.226	0	0.221	0.062	0	0	0	0.012	0
19	32.4121yell	19.5	0.0375	1.655	63.03	0.0405	0	0	0.006	5.295	0.295	0.001	0.9355	0.0335	0	0
	32.4121whitinc1	13.45	0.103	1.53	64.78	0.017	0	0	0	5.37	0.325	0.004	1.7	0.082	0	0
20	32.4121wh	19.52	0.0065	1.425	61.52	0.016	0.0005	0	0.0075	7.815	0.34	0	2.66	0.0605	0.0065	0
	32.4121whitinc2	19.18	0.01	1.31	59.68	0	0	0	0	8.72	0.326	0	5.33	0.088	0	0
21	32.4121pur	15.01	0	1.0445	68.72	0.0095	0.048	0	0.0145	7.665	0.7315	0.0025	0.071	0.0185	0.006	0
22	32.4122_	19.415	0	1.53	61.205	0.013	0.0055	0	0.004	7.92	0.325	0.0015	3.215	0.0855	0.0035	0
	32.4122whitinc	18.95	0.024	1.5	57.75	0.022	0	0	0	8.83	0.315	0.015	7.26	0.158	0	0
23	32.4123_	19.775	0.007	1.41	61.83	0.0165	0.013	0	0.0105	7.705	0.34	0.0095	2.44	0.0875	0.0015	0
	32.4123diffmat1	19.66	0.081	1.64	63.26	0.05	0	0	0	5.36	0.302	0.016	0.576	0.029	0.004	0
	32.4123whitinc1	19	0	1.33	57.55	0.02	0	0	0	8.49	0.305	0	7.17	0.116	0.008	0
	32.4123whitinc2	18.44	0.248	1.43	57.62	0.029	0	0	0	4.72	0.307	0	3.18	0.077	0	0
24	32.4124_	15.08	0.0065	1.0065	68.95	0.0275	0.029	0	0.0145	7.62	0.7185	0.0005	0.0795	0.014	0.0075	0
25	32.410Awh	16.445	0	1.805	60.555	0.0245	0.0415	0	0.001	10.095	0.669	0.002	3.605	0.078	0.005	0
	32.410Awhitinc	15.84	0.004	1.68	57.08	0.033	0.051	0	0	11.05	0.681	0.012	7.71	0.178	0.01	0
26	32.410Ablk	15.34	0.0325	1.525	61.44	1.365	0.0355	0	0.0035	9.345	0.4625	0.0065	0.076	0.0495	0.0095	0.0025
27	32.408l	16.037	0.544	0.536	63.807	0.0377	0.099	0	0.0017	6.1667	1.1023	0.001	0.8633	0.001	0.0003	0
	32.408lwhitinc1	15.41	0.525	0.463	56.09	0.038	0.079	0	0	5.52	0.951	0	5.28	0.092	0	0
	32.408lwhitinc2	14.31	1.45	0.385	47.54	0.046	0.026	0	0.001	5.08	0.854	0	9.02	0.122	0	0
28	32.408ll1	17.295	0.189	2.46	62.145	0.148	0.0185	0	0.0065	7.71	0.484	0.004	0.3595	0.051	0	0
	32.408ll1whitinc	16.62	0.308	2.14	54.1	0.151	0	0	0.009	6	0.403	0.018	5.08	0.091	0	0
29	32.408ll2	17.16	0.02	1.775	61.19	2.33	0.012	0	0.0015	8.52	0.414	0	0.111	0.019	0.0115	0
30	32.413l1	19.95	0	2.965	64.705	0.0015	0.007	0	0.006	5.675	0.4405	0.017	0.196	0.021	0.001	0
	32.413l2	17.11	0.0005	2.43	62.72	0.0035	0.0315	0	0	9.265	0.5485	0	0.9205	0.029	0	0
	32.413l2whitinc	16.21	0	2.16	55.19	0.004	0.014	0	0	10.99	0.573	0.009	11.08	0.209	0.006	0
31	32.413ll	21.925	0.0025	2.205	63.32	0	0.0075	0	0.0015	4.725	0.4715	0.002	0.146	0.0645	0	0
32	32.413lll1	19.225	0.1355	1.004	65.325	0.2825	0.053	0	0.059	6.515	2.06	0.084	0.1495	0.007	0.0045	0
	32.413lll1ltinc	17.41	0.023	0.136	51.43	0.115	0	0	0.02	27.31	0.498	0.019	0.097	0	0.003	0
	32.413lll2	0.8805	0.2575	0.4255	71.965	0.5175	0.125	0	0.062	0.827	3.61	0.136	0.0415	0.1125	0	0

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
17 (cont.)	32.385XXlt	0	0.023	0	0.051	0.006	0.002	0	0	0.019	0	0.114	89.245
	32.385XXwhitinc	0	0.046	0.014	0.256	0	0.025	0.002	0	0.001	0.031	0.038	102.16
18	27.1495All	2.905	0.69	0.201	0.759	0.126	0	0.004	0	0.0085	0.0125	0.1875	98.31
	27.1495IIIwhitinc	0.002	12.59	0.287	0	1.033	0.003	0	0	0.017	0	0.065	98.331
19	32.4121yell	3.04	0.429	0.4235	1.165	0.041	0.007	0	0	3.715	0	0.1595	99.807
	32.4121whitinc1	2.97	0.444	0.389	0.049	0.032	0	0	0	5.31	0.027	0.106	96.687
20	32.4121wh	4.455	0.195	0.4475	0.576	0.0045	0.037	0.005	0	0.013	0.0035	0.129	99.244
	32.4121whitinc2	4.36	0.184	0.425	0.049	0.008	0	0	0	0	0	0.119	99.788
21	32.4121pur	2.54	0.3875	0.2515	0.522	0.746	0	0	0	0	0.0095	0.0835	97.881
22	32.4122_	4.46	0.1915	0.457	0.05	0.023	0.033	0.0055	0	0.05	0.008	0.1215	99.123
	32.4122whitinc	4.21	0.189	0.431	0.542	0.02	0.015	0	0	0.017	0	0.104	100.35
23	32.4123_	4.5	0.1665	0.45	0.293	0.018	0	0	0	0.0315	0.0035	0.121	99.228
	32.4123diffmat1	3.02	0.377	0.379	0.606	0.047	0	0	0	3.48	0	0.157	99.044
	32.4123whitinc1	4.18	0.163	0.433	0.327	0.015	0	0	0	0.516	0.007	0.127	99.757
	32.4123whitinc2	2.84	0.651	0.289	0.567	0.05	0.006	0	0	8.19	0	0.113	98.757
24	32.4124_	2.655	0.385	0.244	0.0545	0.7365	0.008	0	0	0	0.002	0.0885	97.728
25	32.410Awh	4.495	0.3305	0.328	0.332	0.01	0.033	0.008	0.01	0	0.003	0.1105	98.986
	32.410Awhitinc	4.45	0.338	0.334	0.632	0.014	0.006	0.001	0.013	0.021	0.049	0.091	100.28
26	32.410Ablk	4.265	0.3595	0.264	0.466	2.97	0	0.02	0	0.006	0.024	0.0985	98.168
27	32.408l	3.05	0.89567	0.1077	0.7527	0.0677	0.007	0.0093	0.008	5.9633	0.006	0.0387	100.1
	32.408lwhitinc1	2.85	1.44	0.089	0.355	0.035	0.001	0	0	13.07	0	0.07	102.36
	32.408lwhitinc2	2.83	1.45	0.17	0.458	0.067	0	0	0	19.99	0.019	0.048	103.87
28	32.408ll1	4.385	0.3735	0.373	0.438	0.025	0.0085	0.001	0	2.67	0	0.1315	99.277
	32.408ll1whitinc	3.91	0.85	0.3	0.364	0.029	0	0.022	0	11.1	0.023	0.107	101.63
29	32.408ll2	3.97	0.5165	0.345	0.619	1.7	0.0095	0.006	0.0095	0.0105	0.005	0.0955	98.849
30	32.413l1	3.62	0.2295	0.369	0.5465	0.019	0.028	0.0065	0	0.009	0.013	0.228	99.053
	32.413l2	3.52	0.003	0.381	0.1975	0.0065	0.0065	0	0	0.0115	0	0.173	97.357
	32.413l2whitinc	3.25	0.403	0.362	0.358	0.181	0	0.016	0	0	0	0.161	101.18
31	32.413ll	6.12	0.247	0.544	0.7885	0.0285	0	0	0	0	0.0085	0.118	100.72
32	32.413lll1	3.74	0.4475	0.2255	0.394	0.1415	0.007	0	0	0	0.008	0.0835	99.952
	32.413lll1itinc	0.955	0.1	0.01	0.019	0.102	0.007	0	0	0	0.017	0.031	98.303
	32.413lll2	8.045	0.7485	0.0965	0.024	0.1215	0	0.0095	0	0.0075	0.003	0.015	88.03

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2
33	**24.908Ibl**	21.135	0	2	63.55	0	0.0325	0	0.0005	5.69	0.6305	0.0135	0.146	0.039	0.0105	0
34	**24.908Iwh**	20.59	0.006	2.275	62.155	0.004	0.0355	0	0.0035	5.84	0.582	0.008	2.54	0.0625	0.0005	0
	24.908Iwhitinc	18.74	0.004	0.805	16.83	0	0	0	0.006	0.984	0.032	0	58.68	1.362	0.015	0
35	**24.908II**	17.88	0	1.515	62.785	0.0155	0.029	0	0.005	9.345	0.7205	0.004	0.1	0.019	0.0005	0
36	**24.908III**	19.63	0.04	2.165	61.61	2.07	0.0185	0	0.0025	6.955	0.4835	0.0055	0.242	0.054	0	0
	24.908IIIwhitinc	17.61	2.49	1.34	49.73	1.64	0	0	0.007	10.37	0.432	0.009	4.5	0.105	0	0
37	**24.908IV**	16.925	0.1715	1.67	62.48	0.0385	0.0365	0	0.014	6.05	0.6735	0	0.381	0.0345	0.0005	0
	24.908IVwhitinc	11.87	2.1	0.81	30.93	0.061	0	0	0	3.06	0.457	0.012	13.21	0.193	0	0
38	**24.908V**	18.07	0.002	1.86	62.305	1.0115	0.0375	0	0	9.1	0.608	0.0025	0.1545	0.051	0	0
39	**32.407I**	18.46	0	2.285	63.79	0.0015	0.0305	0	0.008	7.875	0.5775	0	0.1535	0.0155	0.0035	0
40	**32.407II**	16.32	0	1.66	60.16	1.59	0.028	0	0.008	8.63	0.555	0	0.11	0.053	0	0
41	**32.407III**	16.745	0.0015	1.875	63.77	0.034	0.024	0	0.008	8.69	0.5275	0	0.3325	0.039	0.0045	0
	32.407IIIwhitinc	15.86	0.035	1.57	53.98	0.012	0.008	0	0.018	6.7	0.522	0.004	6.34	0.072	0	0
42	**32.386I**	17.44	0.0135	2.245	61.85	1.162	0.0235	0	0.0015	7.98	0.5425	0.005	0.1365	0.036	0	0
43	**32.386II**	18.86	0.1175	1.695	59.935	0.744	0.0315	0	0.0675	6.72	2.75	0.0965	0.2795	0.068	0	0
44	**32.386IV**	16.175	0.003	1.33	64.195	0.0025	0.01	0	0.0015	6.74	0.53	0.003	1.99	0.042	0.0065	0
45	**32.386V**	19.605	0.0045	0.679	59.215	0	0.043	0	0.0045	7.43	2.73	0.0075	2.23	0.074	0.006	0
	32.386Vwhitinc	18.34	0	0.671	58.27	0.005	0.036	0	0	7.71	2.72	0.001	4.17	0.09	0.01	0
46	**32.386VI**	14.02	0.004	2.345	62.795	0	0.072	0	0	8.51	0.85	0	0.914	0.0565	0.007	0
	32.386VIwhitinc	7.81	0	1.026	57.72	0.001	0.085	0	0	5.13	1.043	0.003	0.407	0.004	0	10.87
47	**32.395I**	14.185	0.021	2.18	65.385	0.024	0.095	0	0.002	8.885	0.876	0.0055	0.1165	0.014	0.0025	0
48	**32.404I**	18.12	0.114	1.26	61.26	1.212	0.044	0	0	6.23	0.677	0.011	0.552	0.019	0	0
	32.404whitinc1	17.94	0.274	1.19	57.63	1.104	0.035	0	0.013	5.85	0.663	0.001	2.75	0.059	0	0
49	**32.404II**	14.645	0.1865	2.755	61.08	0.413	0.0905	0	0.143	6.715	2.635	0.189	0.305	0.0535	0.002	0
50	**32.404III**	17.465	0	1.6	65.435	1.455	0.05	0	0.0075	6.2	0.6285	0.0025	0.077	0.0115	0.0125	0
51	**Z1184I**	17.97	0.2415	1.09	58.595	0.061	0.064	0	0.102	8.065	3.075	0.1935	0.657	0.0585	0	0
52	**Z1184II**	15.635	0.0135	1.84	59.375	2.03	0.0235	0	0	8.565	0.5955	0.0045	3.49	0.078	0	0
	Z1184IIwhitinc	12.99	0.014	1.26	40.86	1.56	0	0	0	13.45	0.039	0	24.14	0.431	0.01	0
53	**Z1184III**	15.905	0.0065	1.82	59.76	1.975	0.012	0	0.012	8.83	0.5525	0.011	2.64	0.0625	0	0
	Z1184IIIwhitinc	13.5	0	1.07	40.21	1.45	0	0	0.006	14.59	0.152	0.005	27.66	0.544	0.007	0
54	**Z1184IV**	16.26	0.025	2.445	62.825	0.5985	0.047	0	0.0045	7.045	0.653	0	0.2905	0.0435	0.0075	0
55	**Z1184V**	16.63	0.328	0.6215	60.1	0.0065	0.082	0	0.147	8.065	3.845	0.2755	0.851	0.071	0	0

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
33	**24.908Ibl**	4.06	0.34	0.569	0.826	0.1375	0.01	0.004	0	0.0185	0	0.1745	99.386
34	**24.908Iwh**	3.86	0.355	0.47	0.3375	0.0165	0.0135	0.005	0	0.001	0	0.2355	99.395
	24.908Iwhitinc	0.576	0.064	0.29	0.01	0	0	0.036	0.256	0.014	0.025	0.027	98.756
35	**24.908II**	4.78	0.3685	0.18	0.8485	0.028	0.011	0.0085	0.002	0.0025	0.007	0.0915	98.749
36	**24.908III**	3.99	0.297	0.302	0.352	0.0165	0.0145	0.0035	0	0.682	0	0.1635	99.097
	24.908IIIwhitinc	3.75	1.96	0.204	0.039	0.033	0	0	0.029	7.22	0	0.139	101.61
37	**24.908IV**	4.735	0.4845	0.2315	0.3355	0.0315	0.0065	0	0	4.5	0.0035	0.193	98.995
	24.908IVwhitinc	2.56	8.58	0.243	0.383	0.041	0.023	0	0	26.27	0	0.086	100.89
38	**34.908V**	4.05	0.3165	0.322	0.6905	0.016	0.01	0	0.015	0.0145	0.0245	0.1065	98.767
39	**32.407I**	4.135	0.3315	0.371	0.5855	0.0045	0	0.0045	0	0.0005	0.0095	0.1285	98.771
40	**32.407II**	4.75	0	0.377	0.757	0	0.027	0	0	0.003	0	0.118	95.146
41	**32.407III**	3.81	0.34	0.3255	0.2725	0.0085	0	0	0.0095	1.235	0.0025	0.1485	98.205
	32.407IIIwhitinc	3.19	1.222	0.265	0.454	0.022	0.06	0	0	12.51	0	0.121	102.97
42	**32.386I**	4.31	0.352	0.4705	0.7005	1.455	0.0125	0.011	0	0.004	0.0075	0.191	98.95
43	**32.386II**	5.47	0.415	0.3805	0.9095	0.6565	0.0155	0	0	0	0.004	0.1505	99.366
44	**32.386IV**	4.035	0.004	0.354	0.83	0.011	0.007	0	0	0	0	0.11	96.379
45	**32.386V**	4.625	0.1845	0.377	1.015	0.1325	0	0.001	0	0.001	0	0.0885	98.453
	32.386Vwhitinc	4.53	0.004	0.366	0.911	0.003	0	0.002	0.002	0.031	0.021	0.087	97.981
46	**32.386VI**	4.27	0.003	0.329	0.632	0.001	0	0.0035	0	0.0105	0.017	0.14	94.981
	32.386VIwhitinc	2.3	0	0.159	0.569	0	0.023	0.001	0	0.01	0.005	0.099	87.266
47	**32.395I**	3.94	0.507	0.1575	1.285	0.018	0.0005	0.0005	0.0025	0.007	0.0025	0.306	98.017
48	**32.404I**	3.81	0	0.511	0.869	0	0.027	0	0	2.65	0	0.167	97.532
	32.404whitinc1	3.66	0.005	0.451	0.844	0	0.018	0.015	0	6.51	0	0.159	99.171
49	**32.404II**	4.545	0.5885	0.2735	0.789	0.214	0.0035	0.007	0	0.0035	0.005	0.211	95.852
50	**32.404III**	2.915	0.314	0.2815	1.194	0.002	0	0.019	0	0.001	0	0.1555	97.826
51	**Z1184I**	5.715	0.5	0.339	0.8565	0.2215	0.015	0	0.008	0.013	0.014	0.1125	97.968
52	**Z1184II**	4.955	0.298	0.351	0.715	0.0255	0.0295	0.0035	0.004	0	0.002	0.0915	98.125
	Z1184IIwhitinc	4.43	0.053	0.35	0.596	0.017	0	0	0	0.029	0.013	0.023	100.27
53	**Z1184III**	4.965	0.2795	0.349	0.7145	0.025	0.0145	0.0015	0	0.012	0.007	0.1065	98.062
	Z1184IIIwhitinc	4.23	0.105	0.173	0.475	0.025	0.001	0	0.032	0.007	0.011	0.031	104.28
54	**Z1184IV**	4.475	0.337	0.368	0.597	0.02	0	0	0	0.97	0	0.1495	97.161
55	**Z1184V**	5.105	0.6105	0.2675	0.055	0.343	0.0115	0.002	0	0.012	0.0045	0.081	97.514

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2	
56	**24.1307I**	20.025	0.1295	0.9605	62.475	0.0685	0.0445	0	0.0885	6.825	2.015	0.0935	0.1195	0.0295	0.0075	0	0
57	**24.1307IB**	17.94	0.001	1.595	64.26	1.082	0.026	0	0.004	6.905	0.6375	0.0055	1.22	0.0245	0	0	0
58	**24.1307IC**	16.095	0.273	1.73	61.145	0.049	0.0115	0	0.001	6.535	0.4845	0.006	0.6685	0.0475	0	0	0
	24.1307ICwhitinc	13.07	0.518	1.103	38.73	0.021	0	0	0.011	3.93	0.326	0	14.13	0.219	0	0	0
59	**24.1307II**	17.43	0.001	1.81	62.38	0	0.057	0	0.004	8.42	0.729	0	0.1005	0.054	0.0005	0	0
	24.1307IIwhitinc	16.37	0	1.64	59.35	0.033	0.044	0	0.005	7.29	0.637	0	0.092	0.03	0.011	0	0
60	**24.1307IV**	16.19	0	2.51	59.09	1.75	0.058	0	0.006	8.33	0.818	0.004	2.9	0.057	0	0	0
	24.1307IVwhitinc	16.04	0.01	2.3	55.84	1.59	0.058	0	0.002	8.71	0.791	0	9.19	0.174	0	0	0
61	**27.1478_**	22.525	0.2	0.351	56.525	0.0385	0.1915	0	0.099	6.065	5.38	0.305	0.539	0.0735	0	0	0
	27.1478dkpatch	22.53	0.235	0.426	57.76	0.056	0.229	0	0.118	2.65	6.36	0.328	0.647	0.098	0.003	0	0
	27.1478clustinc	21.9	0.062	0.194	52.56	0.006	0.072	0	0.062	16.27	2.91	0.148	0.25	0.023	0	0	0
62	**47.2472B**	18.54	0.0025	2.44	59.055	0.031	0.0405	0	0.002	8.155	0.688	0.001	0.921	0.003	0.0025	0	0
63	**47.2473Ai**	19.82	0.0135	1.335	64.245	0	0.126	0	0.0015	6.2	1.5495	0	0.06	0.0155	0.004	0	0
	47.2473Aihighinc	20.01	0.004	2.05	58.87	0.048	0.07	0	0.006	7.55	1.122	0	2.62	0.084	0	0	0
	47.2473Aiwhitinc1	7.53	0.01	1.28	43.02	0.066	0.085	0	0.002	8.43	0.846	0.001	17.64	0.332	0.008	0	0
64	**47.2473Aii**	19.97	0.0035	0.119	67.405	1.003	0.071	0	0.001	4.915	1.0745	0	0.006	0.016	0	0	0
65	**47.2473Aiii**	20.03	0.01	0.765	63.65	4.27	0.134	0	0	4.47	1.489	0	1.142	0.022	0	0	0
66	**47.2482i**	19.965	0.0215	1.092	63.015	0.595	0.0305	0	0.0155	7.335	1.2005	0.0165	0.0545	0.0325	0	0	0
67	**47.2482ii**	19.895	0.0255	1.0775	62.98	0.606	0.0415	0	0.02	7.255	1.2355	0.021	0.039	0.0125	0.0005	0	0
68	**32.471a**	23.47	0.012	0.8705	58.295	1.0805	0.6855	0.014	0	2.36	6.88	0	2.2	0.0255	0.0035	0	0
	32.471b	23.32	0.005	0.9575	60.42	0.896	0.7205	0	0.005	2.435	7.055	0	0.057	0.02	0.001	0	0
69	**47.2469C**	18.095	0.077	1.146	62.705	0.1475	0.0615	0	0.037	7.425	1.625	0.063	0.145	0.0255	0.0005	0	0
70	**47.2469Eblk**	19.345	0.0075	2.6	60.765	0.027	0.038	0	0.0015	8.54	0.668	0	0.145	0.0255	0.0045	0	0
71	**47.2469Eblu**	20.22	0.419	0.6995	65.555	0.7065	0.0685	0	0.1145	2.58	4.68	0.1775	0.0155	0.0255	0	0	0
72	**47.2469Eyell**	18	0.013	2.12	59.19	0.032	0.027	0	0.003	8.07	0.897	0	0.52	0.0255	0	0	0
	47.2469Eyelllgwhitinc1	8.28	0	0.647	14.59	0.025	0	0	0	2.38	0.331	0	21.5	0.0255	0	0	0
	47.2469Eyelllgwhitinc2	8.53	0	0.642	15.57	0	0	0	0	2.44	0.302	0.007	22.03	0.0255	0	0	0
73	**47.2469Gbll**	19.38	0.033	1.66	63.67	0.3765	0.053	0	0.037	5.665	1.7745	0.048	0.4455	0.035	0.0105	0	0
	47.2469Gbllimat1	1.79	0.045	0.387	79.63	0.197	0.097	0	0.002	0.626	0.759	0.002	0.88	0.078	0	0	0
74	**47.2469Gwhmat1**	18.61	0.01	2.17	62.78	0.068	0.048	0	0	6.26	0.519	0	2.19	0.063	0.001	0	0
	47.2469Gwhmat2	18.25	0.013	2.21	63.8	1.019	0.066	0	0	6.18	0.534	0	1.297	0.053	0	0	0
	47.2469Gwh	18.43	0.0115	2.19	63.29	0.5435	0.057	0	0	6.22	0.5265	0	1.7435	0.058	0.0005	0	0

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
56	**24.1307I**	3.955	0.402	0.2205	0.6685	0.118	0.014	0.011	0.006	0.002	0.011	0.106	98.393
57	**24.1307IB**	3.105	0.365	0.316	0.9055	0.024	0.0095	0	0	0	0.001	0.176	98.603
58	**24.1307IC**	4.185	0.3745	0.289	0.6225	0.0245	0.022	0	0.009	5.66	0.007	0.254	98.494
	24.1307ICwhitinc	2.83	1.51	0.367	0.057	0.049	0.036	0	0	24.93	0	0.108	101.95
59	**24.1307II**	5.065	0.179	0.311	0.9735	0.023	0.0115	0.0095	0	0	0.0005	0.1385	97.699
	24.1307IIwhitinc	4.4	0.3	0.298	0.888	0.018	7.97	0.012	0.013	0.004	0	0.108	99.512
60	**24.1307IV**	4.85	0	0.338	0.532	0.002	0	0.004	0	0.005	0.019	0.166	97.629
	24.1307IVwhitinc	4.69	0	0.339	0.557	0	0	0.003	0	0.022	0	0.151	100.47
61	**27.1478_**	6.07	1.0545	0.282	0.5785	0.229	0.0065	0	0	0.0095	0.0185	0.07	100.61
	27.1478dkpatch	6.87	1.22	0.375	0.822	0.236	0.02	0	0	0	0	0.082	101.06
	27.1478clustinc	3.24	0.501	0.191	0.215	0.175	0	0	0	0.001	0	0.057	98.836
62	**47.2472B**	3.72	0.872	0.3065	0.9945	0.0215	0.003	0.0045	0	3.56	0.005	0.1995	99.568
63	**47.2473Al**	3.09	0.6305	0.5405	1.42	0.028	0.0105	0.0005	0	0.0115	0.0035	0.114	99.22
	47.2473Alhighinc	5.54	0.635	0.338	0.87	0.027	0	0	0	0	0	0.161	100.01
	47.2473Alwhitinc1	3.7	0.507	0.265	0.731	0.019	0.014	0	0.015	0	0.028	0.118	84.649
64	**47.2473Ali**	2.835	0.5635	0.472	0.9815	0.0235	0.0105	0.006	0	0.01	0	0.038	99.525
65	**47.2473Alii**	2.31	0.627	0.473	1.41	0.021	0.015	0	0	0.027	0	0.155	101.02
66	**47.2482I**	4.005	0.4755	0.3895	0.9935	0.1855	0.0015	0	0	0	0.0185	0.1075	99.551
67	**47.2482II**	4.015	0.441	0.3465	1.015	0.198	0.007	0	0	0.0085	0.011	0.0945	99.346
68	**32.471a**	1.2155	1.1625	0.5915	1.47	0.0365	0.046	0.0045	0	0.1795	0.028	0.0555	100.69
	32.471b	1.343	1.2155	0.5475	1.455	0.045	0.0435	0.005	0	0.166	0.018	0.056	100.79
69	**47.2469C**	3.845	0.4415	0.3085	1.1375	0.0815	0.0085	0	0.006	0.018	0.0035	0.105	98.564
70	**47.2469Ebik**	4.46	0.4085	0.448	1.465	0.0175	0.0025	0	0	0.0095	0.0235	0.193	99.665
71	**47.2469Eblu**	2.98	0.2795	0.415	0.923	0.1595	0	0.0025	0	0.015	0.0145	0.065	99.128
72	**47.2469Eyell**	4.77	0.845	0.346	0.968	0.014	0	0.004	0	2.08	0	0.198	98.306
	47.2469Eyelllgwhitinc1	0.582	8.06	0.324	0.162	0	0	0	0.07	38.35	0	0.049	96.73
	47.2469Eyelllgwhitinc2	0.662	8.56	0.134	0.209	0.01	0	0	0.06	37.11	0.029	0.041	97.409
73	**47.2469Gbll**	4.68	0.4985	0.4345	0.719	0.3275	0.0035	0.003	0	0.0085	0.0035	0.1885	100.05
	47.2469Gbllimat1	5.47	0.418	0.254	1.45	0.036	0.002	0	0	0.028	0	0.115	92.267
74	**47.2469Gwhmat1**	5.07	0.281	0.455	1.05	0.024	0.004	0	0	0.012	0.003	0.183	99.799
	47.2469Gwhmat2	5.01	0.31	0.272	0.982	0.027	0.02	0.004	0	0.04	0	0.198	100.28
	47.2469Gwh	5.04	0.2955	0.3635	1.016	0.0255	0.012	0.002	0	0.026	0.0015	0.1905	100.04

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2
74 (cont.)	**47.2469Gwhnoincarea**	18.22	0.014	2.23	62.27	3.47	0.038	0	0	6.21	0.58	0	0.657	0.075	0	0.016
	47.2469Gwhwhitinc	15.08	0	1.75	56.11	0.027	0.026	0	0.004	4.55	0.374	0	0.68	0.043	0.002	0
75	**47.2477Cyell**	4.17	0	0.976	38.16	0	0	0	0	1.236	0.216	0	1.818	0.0255	0	0
76	**32.421AB**	20.915	0	3.03	62.435	0.02	0.032	0	0	5.535	0.3335	0.001	0.211	0.0255	0	0
77	**35.1153_**	20.825	0.0085	2.85	60.46	0.012	0.027	0	0.0005	6.535	0.6515	0	0.178	0.0255	0.0005	0
78	**47.2499Dl**	18.835	0.0115	3.46	60.99	0.01	0.0015	0	0.001	5.645	0.322	0.0005	4.505	0.0255	0	0
79	**47.2499Dll**	18.4	0	2.75	59.86	0.133	0.026	0	0	5.13	0.461	0.004	0.595	0.0255	0	0
80	**35.1172_**	19.045	0.005	0.425	65.355	0.1835	0.097	0	0.0075	6.65	2.275	0.1445	0.0065	0.0255	0.004	0
81	**47.2553AB**	18.995	0	0.1615	66.73	0.494	0.045	0	0	4.365	0.7925	0.003	5.07	0.0495	0.0035	0
	47.2553ABdkptch	1.85	0.007	0.211	90.61	0.13	0	0	0	1.236	0.009	0.001	0.231	0	0	0
82	**47.2208A**	14.45	0.006	2.84	67.915	0.0165	0.066	0	0.006	6.27	1.9	0.0775	0.1595	0.1265	0.002	0
83	**47.2123AB**	18.075	0.009	1.27	61.435	0.0025	0.6155	0.0005	0.0035	4.275	8.68	0.0005	0.0675	0	0.0065	0
	47.2123ABldkinc	11.09	0	0.644	61.5	0.007	0	0.042	0.011	0.539	22.34	0	0.04	0	0.003	0
84	**47.2133i**	0.399	0.008	1.175	69.94	0.054	0.116	0.009	0.004	3.77	2.6	0	2.48	0.0255	0	0
	47.2133ilowinc	0.34	0	1.22	63.21	0.07	0.104	0	0.004	8.63	2.6	0	0.186	0.031	0.004	0
85	**47.2133ii**	16.73	0.005	4.33	61.895	1.226	0.0795	0	0.003	5.12	2.23	0.003	0.2975	0.015	0.007	0
	47.2133iiwhitinc	0.502	0	0	49.11	0.906	0	0	0	2.61	1.67	0.002	0	0.072	0	32.84
86	**47.2133iii**	13.98	0	4.155	58.25	0.0415	0.0905	0	0	4.91	2.25	0	2.095	0.0615	0.0005	0
	47.2133iiifeat	1.89	0	0.32	5.14	0.073	0	0	0	1.233	0.211	0.117	0.142	0.033	0.01	0
	47.2133iiiwhitinc	11.34	0	3.23	49.23	0.024	0.049	0	0	4.29	2.01	0.002	7.69	0.167	0	0
87	**47.2082_**	15.19	0.0085	4.015	57.425	1.1885	0.143	0	0.0005	5.38	3.83	0	1.715	0.085	0.0095	0
	47.2082whitinc1	3.57	0	0.778	14.21	0.51	0.025	0	0.004	5.2	1.449	0	36.18	0.678	0	0
88	**47.2046_**	1.39	0	3.02	76.59	0.037	0.231	0	0	0.403	5.36	0.005	1.067	0.0255	0	0
	47.2046_	1.86	0.0095	3.205	73.985	0.034	0.196	0	0.001	0.486	4.905	0	1.636	0.028	0.003	0
	47.2046whitinc1	1.58	0.002	1.6	24.62	0.072	0	0	0	9.3	1.92	0	0.195	0	0	0
	47.2046crys1	1.65	0.01	2.83	65.2	0.044	0.191	0	0.006	2.45	4.79	0	0.959	0.005	0.002	0
89	**47.2087_4i**	0.6255	0.019	1.52	69.135	0.089	0.139	0	0.004	4.19	2.54	0.004	0.1145	0.053	0.0055	0
	47.2087_4iwhitinc1	1.93	0.016	1.57	59.19	0.126	0.137	0	0	3.27	2.11	0.001	0.134	0.056	0.007	0
90	**47.2087_4ii**	0.988	0.0125	1.87	68.23	0.0635	0.1575	0	0.0005	3.44	2.975	0	5.26	0.093	0.003	0
	47.2087_4iiwhitinc2	0.381	0.015	1.33	65.66	0.048	0.149	0	0.009	4.65	2.54	0.009	4.91	0.099	0	0
91	**47.2087_8i**	16.56	0.0045	4.425	50.88	0.1	0.07	0	0.001	5.64	3.565	0.005	2.73	0.061	0	0
92	**47.2087_8ii**	17	0.0085	4.34	52.02	1.34	0.0895	0	0.007	6.45	4.03	0.0025	2.287	0.068	0.006	0

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
74 (cont.)	**47.2469Gwhnoincarea**	5.1	0.307	0.392	1.07	0.035	0	0	0	0.035	0.021	0.224	100.97
	47.2469Gwhwhitinc	3.75	0.217	0.226	0.772	0.03	18.14	0.012	0	0.01	0.014	0.095	101.91
75	**47.2477Cyell**	0.2565	1.0435	0.146	0.945	0.075	0.0025	0	0	48.2	0.0055	0.1265	98.826
76	**32.421AB**	4.205	0.2175	0.7945	1.235	0.0305	0	0.002	0	0	0.0035	0.222	99.271
77	**35.1153_**	6.215	0.2885	0.5325	1.275	0.0185	0	0.0055	0	0.016	0.006	0.175	99.368
78	**47.2499Dl**	4.42	0.172	0.4575	0.8185	0.0195	0.014	0.0015	0	0.006	0.025	0.219	99.095
79	**47.2499Dll**	4.89	0.663	0.358	0.963	0.035	0.002	0	0	3.86	0.015	0.209	98.301
80	**35.1172_**	0.95	1.252	0.383	0.9655	0.0705	0.0045	0.0005	0	0.533	0.02	0.049	97.62
81	**47.2553AB**	0.2445	0.3345	0.357	1.69	0.0135	0.009	0	0	0.017	0.0095	0.046	99.429
	47.2553ABdkptch	0.038	0.033	0.208	0.309	0	0	0	0	0	0.008	0	94.882
82	**47.2208A**	0.5365	0.4985	0.132	0.063	0.3075	0.001	0.001	0	0.048	0.013	0.2595	95.695
83	**47.2123AB**	1.617	1.65	0.3715	0.9095	0.0735	0.017	0.012	0	0.0015	0.0075	0.1215	99.221
	47.2123ABldkinc	0.088	0.139	0.176	0.106	0	0.035	0	0	0	0.018	0	96.777
84	**47.2133l**	5.56	0.986	0.396	0.13	0.046	0.003	0	0	0.015	0	0.373	88.443
	47.2133llowinc	4.42	0.794	0.659	0.126	0.06	0.015	0.002	0	0.013	0	0.697	83.185
85	**47.2133ll**	3.41	0.7575	0.3475	0.687	0.0435	0.0095	0.0035	0	0.0265	0	0.465	97.692
	47.2133llwhitinc	6.87	0.637	0.179	0.239	0.053	0.001	0	0	0.016	0	0.276	95.984
86	**47.2133lll**	3.695	1.545	0.317	0.594	0.0435	0.013	0.01	0	5.045	0.004	0.4235	97.524
	47.2133lllfeat	1.529	76.64	0.655	0.093	0.024	0	0.005	0	2.06	0	0.8	90.974
	47.2133lllwhitinc	3.11	2.24	0.221	0.5	0.036	0.004	0.004	0	13.47	0	0.429	98.048
87	**47.2082_**	5.42	1.3875	0.307	0.8625	0.0425	0.0055	0.01	0	1.0025	0.009	0.3405	98.376
	47.2082whitinc1	2.89	0.904	0.03	0.263	0.043	0.003	0	0.126	28.27	0.055	0.407	95.596
88	**47.2046_**	0.952	2.39	0.194	1.55	0.158	0.007	0.074	0	1.4	0.014	0.029	94.521
	47.2046_	1.0565	2.265	0.1325	1.65	0.176	0.006	0.0875	0	2.285	0.0275	0.0355	94.071
	47.2046whitinc1	0.547	0.915	1.187	3.34	0.787	0.012	0.25	0.21	33.21	0.474	12.99	93.21
	47.2046crys1	1.8	2.15	0.303	1.47	0.302	0.023	0.085	0	5.4	0.14	1.465	91.275
89	**47.2087_4l**	5.115	0.975	0.509	0.6715	0.046	0	0.0095	0	0.001	0	0.565	86.332
	47.2087_4lwhitinc1	5.39	0.818	0.374	0.823	0.029	12.29	0.009	0	0	0.017	0.786	89.085
90	**47.2087_4ll**	3.715	1.0485	0.2815	1.075	0.0275	0.0125	0.0155	0	0.01	0.017	0.328	89.624
	47.2087_4llwhitinc2	4.36	0.943	0.332	0.659	0.044	0.019	0.007	0	0	0.007	0.458	86.629
91	**47.2087_8l**	4.645	1.92	0.2355	0.729	0.0465	0.0085	0.001	0	5.625	0.013	0.5275	97.793
92	**47.2087_8ll**	4.74	1.1915	0.3	0.723	0.0505	0.0095	0.0085	0	3.49	0.008	0.5155	98.685

Appendix 2
Table 2

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2	
92 (cont.)	**47.2087_8iiwhitinc1**	9.94	0.012	1.86	24.36	0.564	0.052	0	0	11.18	2.17	0	28.93	0.537	0	0	0
	47.2087_8iiwhitinc2	11.54	0.019	2.31	29.8	0.677	0.038	0	0	8.6	2.52	0	20.84	0.348	0	0	0
93	**47.1964i**	22.32	0.005	0.472	63.06	0.007	0.15	0	0.0025	4.92	2.315	0.001	0.0275	0	0	0	0
94	**47.1964ii**	20.56	0.0065	0.3965	61.045	0.041	0.1275	0	0.002	4.01	2.04	0.002	2.945	0.0415	0	0	0
95	**47.1965I**	16.625	0	0.212	63.5	0.0195	0.0715	0	0	7.88	0.486	0.011	0.016	0	0.0055	0	0
	47.1965Idkinc	0.133	0.009	0.014	96.53	0	0	0	0	0.072	0	0.014	0	0.005	0	0	0
	47.1965Iwhitinc	17.44	0.009	0.163	52.56	0.009	0.052	0	0	6.67	0.406	0.038	0.021	0	0.006	0	0
96	**47.1965I23**	16.613	0.0047	0.2043	63.3	0.0087	0.0713	0	0.0007	7.8233	0.4943	0.0133	0.006	0	0	0	0
97	**47.1965II**	17.94	0.002	0.391	63.45	0.003	0.048	0	0	10.45	0.816	0	0.116	0	0.011	0	0
98	**47.1965A**	14.27	0.0025	0.7055	68.365	1.645	0.0195	0	0.0005	7.545	2.08	0.013	1.3835	0.0065	0.0005	0	0
	47.1965Altgr	0.665	0.008	0.067	35.63	0.084	0.395	0.337	0	42.19	7.51	0	0.734	0	0.001	0	0
	47.1965Awhitinc	13.29	0	0.511	52.74	1.3	0	0	0	9.1	1.66	0.016	23.11	0.391	0.008	0	0
99	**47.1965B1**	12.925	0.006	0.694	61.32	0.054	0.019	0	0	9.84	2.275	0.0105	7.365	0.085	0.0015	0	0
	47.1965B1whitinc	12.21	0	0.573	53.22	0.047	0	0	0	11.79	1.96	0.012	16.17	0.248	0	0	0
100	**47.1965B2**	14.28	0.001	0.518	64.49	1.77	0.006	0	0	8.6	2.22	0	1.73	0	0	0	0
	47.1965B2whitinc	8.48	0	0.568	42.29	0.886	0	0	0	9.91	2.7	0	27.12	0.517	0	0	0
101	**47.1965Cnoincl**	14.355	0	0.452	68.53	1.0255	0.022	0	0	8.375	2.355	0.002	0.2275	0	0.0065	0	0
	47.1965Cincrich	14.63	0.017	0.39	64.77	2.53	0.0205	0	0.0005	8.345	2.255	0	2.73	0.0315	0.0075	0	0
	47.1965Cwhitinc	14.37	0	0.385	62.4	1.35	0.02	0	0.009	9.39	2.29	0.003	6.63	0.108	0	0	0
	47.1965grinc	10.02	0	0.306	76.97	1.118	0.009	0	0	5.94	1.408	0	1.018	0	0.007	0	0
	47.1965Clgcrys	9.52	0.003	0.293	59.96	1.002	0.034	0	0	23.02	2.07	0	0.544	0	0	0	0
	47.1965Clgcrysb	7.97	0	0.229	58.61	0.744	0	0	0.005	28.06	1.207	0	0.284	0	0.008	0	0
102	**47.1965E1_**	12.735	0	0.4245	55.525	0.0375	0	0	0.007	7.445	1.93	0	1.825	0	0	0	0
	47.1965E1inc1	11.85	0	0.36	47.99	0.029	0	0	0	6.39	1.647	0.001	6.92	0.021	0	0	0
	47.1965E1inc2	11.95	0	0.325	49.67	0.217	0	0	0.006	6.75	1.666	0	5.27	0.007	0	0	0
103	**47.1965E23_**	15.605	0.007	0.357	65.52	1.97	0.0065	0	0.002	8.14	2.23	0	1.134	0.02	0.0035	0	0
	47.1965E23gr	0.0165	0	0.013	96.775	0.0375	0	0	0.004	0	0	0	0	0	0.0005	0	0
	47.1965E23dkgr	0.49	0	0.815	74.12	0.122	0.074	0	0	1.97	4.54	0.02	0.773	0	0.007	0	0
104	**47.1965JI**	16.71	0.01	0.445	69.295	0.112	0.0135	0	0	5.59	1.8265	0.037	0.0105	0	0	0	0
105	**47.1965JII**	16.55	0.077	0.6	67.12	0.297	0.006	0	0	7.31	2.26	0.151	0.342	0	0.001	0	0
106	**47.1965JIII**	17.35	0.0135	0.4195	66.725	0.117	0.017	0	0	7.435	2.255	0.18	0.1525	0	0	0	0
	47.1965JIIIwhitinc	5.27	0.004	0.16	22.02	0.052	0.012	0	0	5.05	0.696	0.034	0.032	0.264	0	0	0

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
92 (cont.)	**47.2087_8iiwhitinc1**	2.21	0.891	0.236	0.401	0.022	0.016	0	0.069	13.73	0	0.217	97.397
	47.2087_8iiwhitinc2	2.69	1.114	0.173	0.436	0.033	0	0	0.047	15.27	0	0.294	96.749
93	**47.1964i**	2.47	1.0015	1.063	1.02	0.034	0.004	0.001	0	0.016	0	0.047	98.936
94	**47.1964ii**	2.09	1.48	0.7315	0.792	0.027	0.0055	0.0015	0	3.425	0.0155	0.041	99.826
95	**47.1965I**	0.5175	7.03	0.2805	0.9495	0.031	0.0005	0.004	0	0.002	0.0125	0.06	97.715
	47.1965Idkinc	0.059	0.188	0.007	0	0	0	0.008	0	0.013	0	0.009	97.061
	47.1965Iwhitinc	0.505	20.99	0.166	0.812	0.045	0.048	0	0	0.027	0.012	0.033	100.01
96	**47.1965I23**	0.50667	7.42	0.2533	0.86	0.0427	0.034	0.0063	0	0.0063	0.0107	0.0603	97.74
97	**47.1965II**	0.704	2.57	0.245	0.908	0.024	0.04	0.01	0	0.015	0	0.036	97.78
98	**47.1965A**	0.4335	0.1535	0.165	0.5035	0.012	0.005	0.0045	0	0.1555	0.0035	0.056	97.529
	47.1965Altgr	2.08	4.14	0.099	0	0.066	0	0	0	0	0.034	2.218	96.259
	47.1965Awhitinc	0.296	0.252	0.213	0.71	0.007	0	0.003	0	0.145	0.009	0.018	103.78
99	**47.1965B1**	0.657	0.492	0.3125	0.3515	0.002	0.0085	0.0115	0	1.53	0	0.0815	98.043
	47.1965B1whitinc	0.543	0.429	0.282	0.47	0	0.011	0.018	0	1.47	0	0.046	99.498
100	**47.1965B2**	0.494	0.308	0.184	0.83	0	0.055	0	0	1.44	0.007	0.08	97.011
	47.1965B2whitinc	0.377	0.306	0.223	0.366	0	0.019	0	0	1.31	0	0.039	95.111
101	**47.1965Cnoincl**	0.483	0.259	0.157	1.14	0.0105	0	0.0065	0	0.015	0.006	0.0435	97.471
	47.1965Cincrich	0.4735	0.425	0.1515	0.976	0.015	0.0045	0.0195	0	0.1695	0	0.046	98.008
	47.1965Cwhitinc	0.45	0.32	0.284	1.13	0.039	0.019	0	0	0.021	0.006	0.045	99.268
	47.1965grinc	0.295	0.248	0.13	0.062	0.017	0.049	0	0	0.021	0	0.019	97.636
	47.1965Clgcrys	0.373	0.278	0.094	0.648	0.029	0	0	0	0.023	0	0.076	97.966
	47.1965Clgcrysb	0.292	0.192	0.088	0.527	0.021	0.005	0.007	0	0.018	0	0.217	98.483
102	**47.1965E1_**	0.4205	0.7635	0.2235	0.669	0.0205	0	0.0095	0	15.485	0.002	0.0325	97.555
	47.1965E1inc1	0.345	1.48	0.182	0.624	0.005	0	0.001	0	21.29	0	0.042	99.178
	47.1965E1inc2	0.36	1.29	0.208	0.586	0.025	0	0.008	0	19.36	0.001	0.028	97.725
103	**47.1965E23_**	0.482	0.3055	0.1665	1.23	0.0105	0	0.0015	0	0.146	0.0075	0.0585	97.404
	47.1965E23gr	0	0.011	0.0075	0.0035	0	0	0.0075	0	0.002	0.013	0.006	96.897
	47.1965E23dkgr	0.249	0.662	0.414	0.142	0.001	0.041	0	0	0.03	0.001	0.031	84.502
104	**47.1965JI**	0.6895	0.39	0.489	0.4795	0.001	0.0185	0.01	0	0.0035	0.0085	0.038	96.178
105	**47.1965JII**	0.559	1.47	0.469	0.655	0.02	0	0.001	0	0.111	0.01	0.04	98.05
106	**47.1965JIII**	0.6345	0.5495	0.3115	0.7065	0.0175	0	0.004	0	0	0.007	0.0495	96.944
	47.1965JIIIwhitinc	0.176	0.006	0.323	0.705	0	0.007	0.001	0	1.86	0	0.071	36.742

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		Na2O	ZnO	K2O	SiO2	CuO	TiO2	BaO	NiO	CaO	Al2O3	CoO	Sb2O5	As2O5	Ag2O	SnO2
106 (cont.)	**47.1965JIIIwhitinc2**	12.3	0	0.068	42.89	0	0.293	0	0	13.89	1.272	0.046	0.022	0	0	0
107	**47.1965JIV**	16.918	0.0035	0.3273	66.843	0.066	0.0235	0	0.0058	7.97	1.987	0.1208	0.6053	0	0	0
108	**47.1965JV**	15.84	0.0105	0.254	69.555	0.0815	0.019	0	0.0075	6.83	1.5435	0.1665	0.871	0	0	0
109	**47.2006Ai**	0.3855	0.001	0.0865	6.535	0.143	0	0	0.002	2.39	0.25	0.082	0	0	0.004	0
110	**47.2006Aii**	0.6705	0.001	0.0795	8.33	3.725	0	0.0645	0	18.63	0	0.039	0.021	0	0	0
111	**47.2006Aiii**	1.11	0.002	0.4075	5.925	4.645	0	0.019	0.002	3.99	0	0.0325	0.016	0	0.0085	0
112	**47.2006Abl**	17.51	0	0.437	67.81	1.86	0.08	0	0	6.09	2.05	0.01	0.046	0	0.005	0
113	**47.2002_**	16.5	0.005	0.383	65.645	0.034	0.02	0	0	8.135	2.43	0	3.305	0	0	0
	47.2002dkptch1	0.16	0	0.008	93.41	0	0	0	0	0.02	0	0	0	0	0	0
	47.2002whitinc1	15.89	0.001	0.305	48.31	0.023	0	0	0	7.23	1.702	0.009	13.23	0.187	0	0
114	**47.1995_**	12.77	0.0035	3.165	61.875	0.0215	0.1465	0	0.001	6.485	3.085	0	0.154	0.0165	0.007	0.095
	47.1995whitinc1	7.5	0	0.433	26.56	0.01	0	0	0.001	3.25	1.201	0	0	0.024	0	15.94
	47.1995feat	11.31	0	2.21	49.91	0.006	0.07	0	0.01	5.11	2.41	0.003	0.082	0.058	0	2.16
115	**47.1999i**	15.64	0.0315	0.9465	63.67	0.1495	0.0245	0	0.0035	7.98	2.295	0.0625	0.5485	0.002	0.001	0
116	**47.1999ii**	14.07	0	0.5835	58.835	0.018	0.019	0	0.0005	9.2	2.195	0.0015	5.94	0.0355	0	0
	47.1999iiwhitinc1	13.64	0.013	0.529	53.67	0.015	0.007	0	0	11.06	2.04	0	14.07	0.19	0	0
117	**TBz1II**	15.805	0.008	0.9565	47.845	0.004	0.115	0	0.0025	8.465	2.185	0.001	0.071	0	0.004	0
118	**TBz2IV**	0.757	0.012	0.377	74.02	0.002	0.001	0	0.001	0.366	0.474	0	0.026	0	0.003	0
119	**TBz2V**	13.675	0.0015	1.91	53.625	0.0015	0.027	0	0.0005	4.085	1.3185	0	0.112	0.0625	0	0
120	**DAAI2**	0.0355	0.0015	0.434	57.6	1.223	0.0225	0	0.0005	5.275	0.9265	0	0.013	0.062	0.009	0
121	**DAAI3**	14.15	0.0015	0.6815	52.895	0.0025	0.0165	0.0005	0.0005	8.45	1.8695	0.001	0.0405	0	0.004	0
122	**DAAI4**	12.11	0	0.468	48.325	1.34	0.023	0	0.002	5.49	1.764	0	0.033	0	0	0.0545
	DAAI4whi	12.1	0	0.475	49.19	1.33	0.005	0	0	5.35	1.74	0	0.043	0	0	0.047
	DAAI4dar	12.27	0.006	0.481	48.35	1.31	0.011	0	0	5.54	1.781	0	0.033	0	0	0.048
123	**DAAIIA**	0	0.0975	0.0325	0.202	121.19	0	0.0015	0.2265	0.002	0	0.203	0.027	0	0.029	0

Appendix 2
Table 2

Results of Electron Microprobe Analysis

		MgO	FeO	SO3	Cl	MnO	ZrO2	Cr2O3	SrO	PbO	V2O5	P2O5	Total
106 (cont.)	**47.1965JIIIwhitinc2**	0.368	29.21	0.238	0.724	0.044	0.023	0.002	0	0.064	0.081	0.762	102.3
107	**47.1965JIV**	0.596	0.632	0.2098	0.844	0.0105	0.0008	0.007	0	0.021	0.01	0.0368	97.237
108	**47.1965JV**	0.377	0.6595	0.097	1.435	0.0075	0	0	0	0.0095	0.01	0.0235	97.798
109	**47.2006AI**	0.772	61.515	0.2345	0.341	0.001	0.0115	0.003	0	0.0125	0.016	5.315	78.1
110	**47.2006AII**	1.055	31.495	0.4035	0.28	0	0.0435	0.002	0	0.0105	0.015	18.425	83.292
111	**47.2006AIII**	0.492	24.735	0.1575	0.4455	0.005	0.025	0.002	0.033	0.002	0	16.01	58.065
112	**47.2006AbI**	0.574	0.505	0.297	0.916	0.012	0.018	0.008	0	0.015	0.01	0.065	98.316
113	**47.2002_**	0.6375	0.361	0.3315	0.7905	0.0115	0.0025	0	0	0.0705	0.011	0.0435	98.717
	47.2002dkptch1	0	0.087	0.026	0.011	0	0.003	0.004	0	0.01	0.007	0.022	93.767
	47.2001whitinc1	0.372	11.19	0.695	0.741	0.003	0	0.002	0	0.063	0.024	0.572	100.55
114	**47.1995_**	3.43	0.8645	0.177	0.6465	2.18	0.024	0.007	0	2.429	0	0.2065	97.79
	47.1995whitinc1	1.462	1.4	0.051	0.398	0.964	0.004	0	0	39.37	0	0.05	98.619
	47.1995feat	2.8	1.38	0.139	0.615	1.8	0.025	0.005	0	16.7	0.02	0.164	96.986
115	**47.1999I**	0.7325	0.514	0.211	0.9445	3.045	0.0005	0	0	0.6885	0.005	0.083	97.579
116	**47.1999II**	0.6375	0.3385	0.4705	0.4755	0.2845	0	0	0	6.005	0.0045	0.0825	99.196
	47.1999IIwhitinc1	0.565	0.296	0.416	0.415	0.264	0	0.001	0	5.4	0.016	0.073	102.68
117	**TBz1II**	0.874	0.8375	0.262	0.6325	2.605	0.0225	0	0	0.033	0.021	0.1185	80.87
118	**TBz2IV**	0.053	0.176	0.12	0.836	0.004	0	0.006	0	0	0	0.011	77.243
119	**TBz2V**	5.245	0.32	0.226	0.714	0.042	0.0015	0.004	0	0.0055	0	0.0815	81.459
120	**DAAI2**	4.175	0.4605	0.3295	0.3435	0.0335	0.009	0.002	0	0	0.0145	0.2675	71.237
121	**DAAI3**	0.4565	0.283	0.1795	0.951	0.5015	0.006	0	0	0.002	0.0045	0.0795	80.576
122	**DAAI4**	0.3135	1.1585	0.1175	0.8505	0.013	0.011	0.001	0	11.695	0	0.0545	83.823
	DAAI4whi	0.274	1.25	0.068	0.857	0.005	0	0	0	12.8	0.027	0.077	85.637
	DAAI4dar	0.308	1.114	0.124	0.858	0.004	0.004	0.008	0	10.95	0.014	0.073	83.287
123	**DAAIIA**	0	0.014	0.76	0.0195	0.0035	0	0	0	0	0.0045	0.941	123.75

Appendix 2
Table 3

Results of Image Analysis (samples with evidence of internal heterogeneity only)

Sample	Colour	Opaque?	space covered by inclusions (in pixels)	number of inclusions in area imaged
24.1307IB	turquoise	Y	18292	333
24.1307IC	yellow	Y	29043	134
24.1307IV	turquoise	Y	52615	990
24.908I	white	Y	205137	673
24.908III	green	N	8780	16
24.908IV	yellow	Y	30390	94
27.1495III	red	Y	22297	98
32.385II	green	Y	22092	219
32.385IV	blue	N	7663	36
32.385IX	green	N	7219	57
32.385V	green	N	21013	155
32.385VII	turquoise	Y	53013	465
32.385VIII	turquoise	Y	1058	19
32.385X2	green	N	2567	26
32.385XIII	green	Y	18354	84
32.385XIV	green	Y	13131	40
32.385XV	blue	N	9816	149
32.385XVI	turquoise	Y	14993	257
32.386IV	turquoise	Y	53961	667
32.386V	blue	N	64631	594
32.386VI	turquoise	Y	18461	268
32.404I	green	Y	24943	184

Appendix 2
Table 3

Results of Image Analysis (samples with evidence of internal heterogeneity only)

Sample	Colour	Opaque?	space covered by inclusions (in pixels)	number of inclusions in area imaged
32.407III	yellow	Y	21904	99
32.408I	yellow	Y	55765	155
32.408II	yellow	Y	35989	102
32.410A	white	Y	51111	380
32.4121_white	white	Y	82057	989
32.4121_yell	yellow	Y	46138	190
32.4122_	white	Y	72701	751
32.4123_	yellow	Y	69401	980
32.4123_diff area	yellow	Y	54733	152
32.413I2	white	Y	38595	196
32.471a_	white	Y	75367	642
47.1964ii_	yellow	Y	84694	655
47.1965A	turquoise	Y	28757	90
47.1965B1	white	Y	278943	6063
47.1965B2	turquoise	Y	44715	580
47.1965Cincrich	turquoise	Y	51786	710
47.1965E1_	yellow	Y	221686	1885
47.1965E23_	turquoise	Y	64862	565
47.1995_	green	N	16699	44
47.1999ii_	white	Y	204298	2578
47.2002_	white	Y	65816	1113
47.2046_	yellow	Y	68650	301
47.2082_	yellow	Y	49372	559

Appendix 2

Results of Image Analysis (samples with evidence of internal heterogeneity only)

Table 3

Sample	Colour	Opaque?	space covered by inclusions (in pixels)	number of inclusions in area imaged
47.2087_4ii_	white	Y	128162	2226
47.2087_8i_	yellow	Y	33479	414
47.2087_8ii_	turquoise	Y	30088	70
47.2133i_	white	Y	32166	483
47.2133iii_	yellow	Y	57446	386
47.2469_Gwh_	white	Y	54853	794
47.2469Eyell_	yellow	Y	52480	109
47.2472B_	yellow	Y	44999	111
47.2473Ai_	white	Y	67583	926
47.2473Aiii_	red	Y	32487	987
47.2477Cyell_	yellow	Y	36938	154
47.2499Di_	white	Y	106987	622
47.2499Dii_	yellow	Y	58481	130
47.2553AB_	white	Y	78019	586
Z1184I	blue	N	7144	140
Z1184II	turquoise	Y	69559	277
Z1184III	turquoise	Y	38897	314
Z1184IV	turquoise	Y	3601	6
Z1184V	blue	N	25819	179